

A search for charged lepton flavor violation in muon to electron conversion



Andrei Gaponenko

2013-12-12

Outline

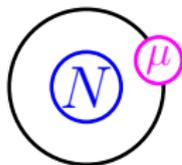
- What and why we measure
or introduction to charged lepton flavor violation
(*Focus on searches with muons — there are also τ , Z , ...*)
- How we do it
 - The concept of $\text{Mu}2e$ measurement
 - The challenges—and how we handle them
- Status

Introduction

Mu2e searches for

Coherent muon to electron
conversion on nucleus

$$\mu^- N \rightarrow e^- N$$



- Initial state is a bound muon
- Nucleus participates in the process
- But remains intact in the end

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Mu2e searches for

Coherent muon to electron
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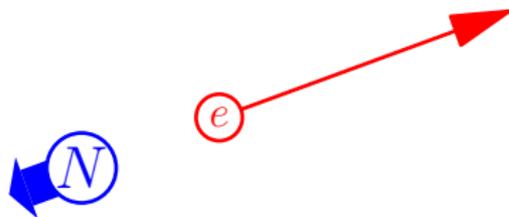
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Compare to

Normal muon decay:

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Flavor violating decay

$$\mu^- \rightarrow e^- \gamma$$

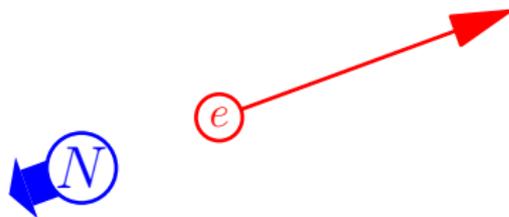


Introduction

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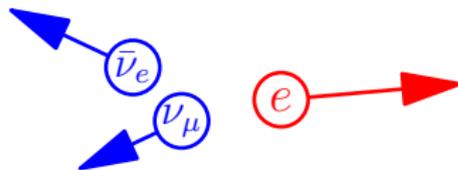
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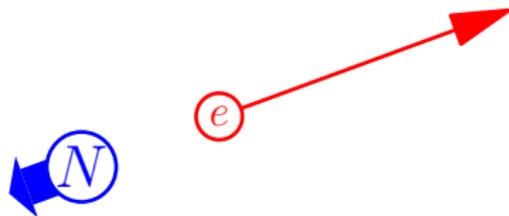


Introduction

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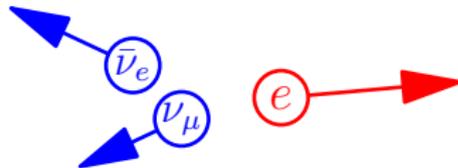
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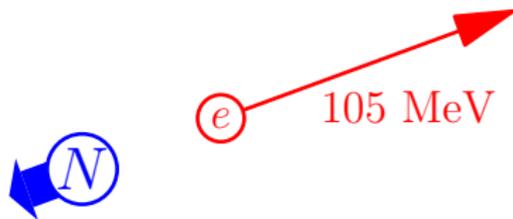


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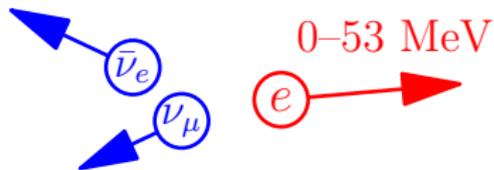
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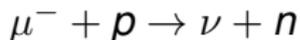


The number we measure

- **Signal:** coherent muon to electron conversion on nucleus
- **Normalization:** all nuclear captures
 - reduces theory uncertainty (nuclear wavefunction cancels)

$$R_{\mu e} = \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)^*]}$$

Simplest capture example:

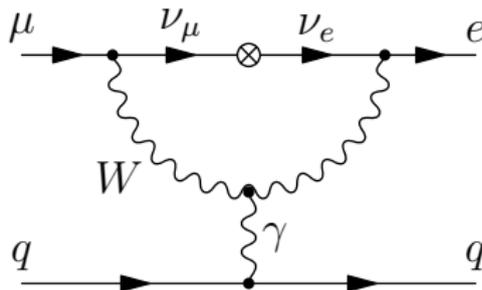


Charged lepton flavor violation

- Neutral lepton flavor violation has been observed

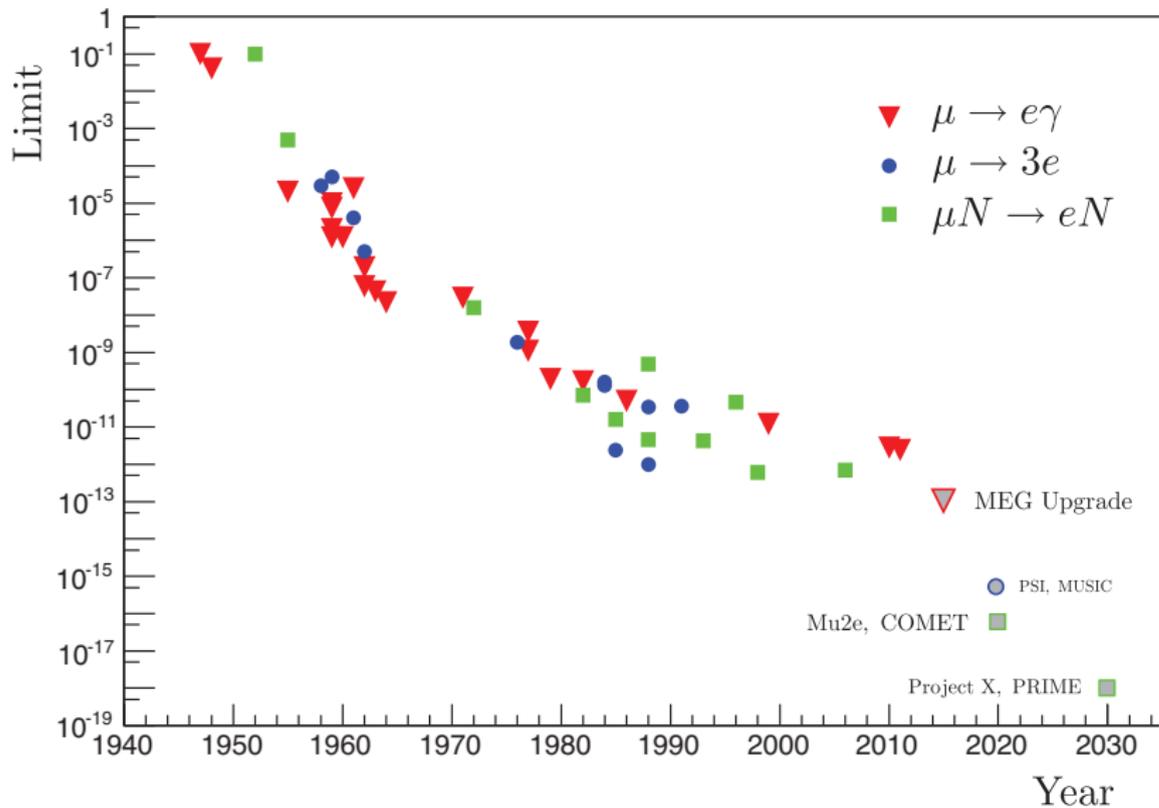


- Induces CLFV



- Induced rate: about 40 orders of magnitude below experimental limits
- CLFV observation would still be an unambiguous proof of New Physics

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$



R. H. Bernstein, P. S. Cooper
Phys. Rept. **532** (2013) 27

CLFV history

Concept of generations

- Muon is not an excited electron
- $\mu \rightarrow e\gamma$ limits:
 $\nu_e \neq \nu_\mu$ hypothesis

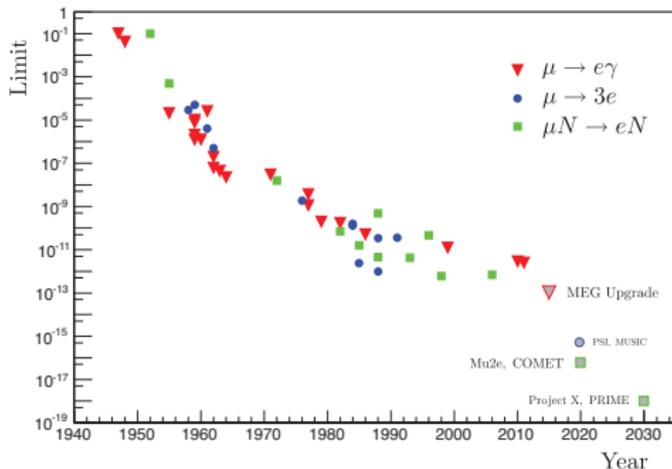
Constraints on models of new physics

Today's best limits

$$R_{\mu e} < 7 \times 10^{-13} \text{ SINDRUM-II 2006}$$

$$Br(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13} \text{ MEG 2013}$$

$$Br(\mu \rightarrow 3e) < 1 \times 10^{-12} \text{ SINDRUM-I 1988}$$



Mu2e goal

Single event sensitivity

$$R_{\mu e} = \text{few} \times 10^{-17}$$

CLFV history

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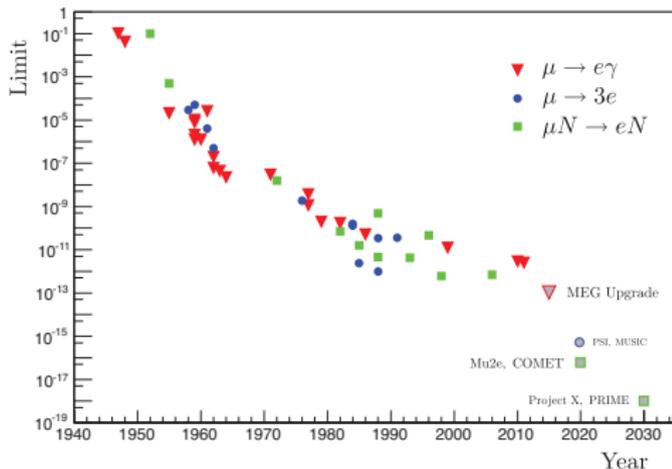
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Mu2e goal

100x better sensitivity

$$R_{\mu e} < 7 \times 10^{-17}$$

Relevancy in the LHC era?

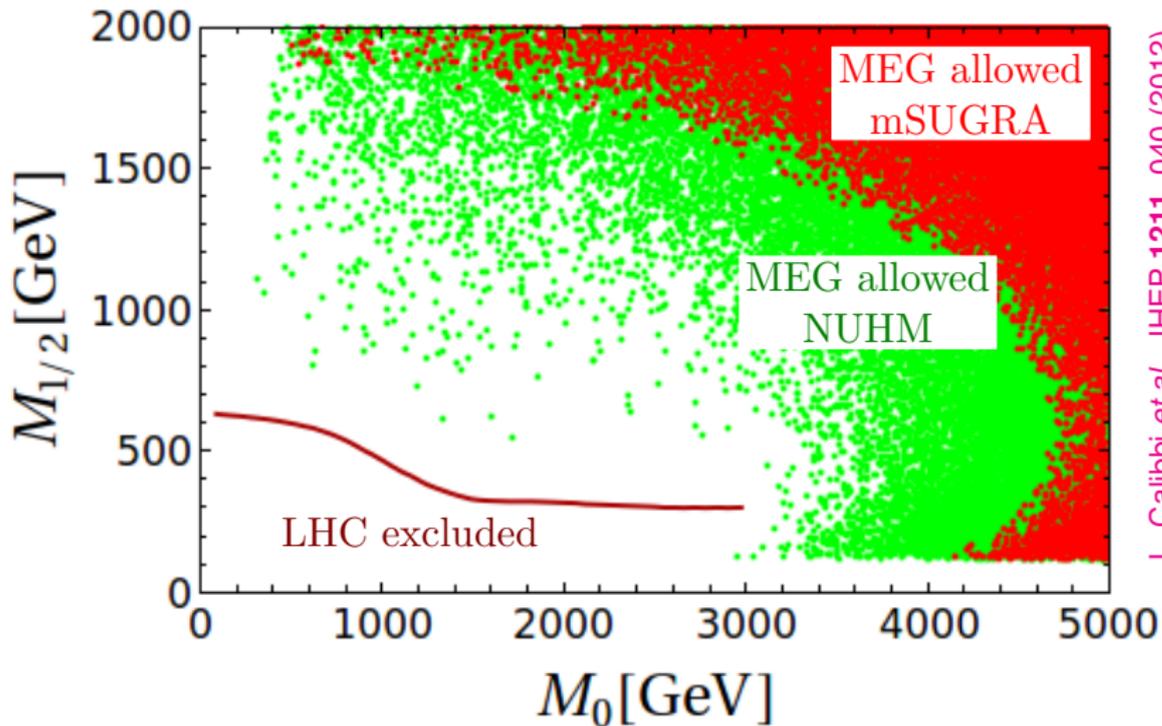


CLFV vs direct LHC searches

An example

- SUSY seesaw GUT models
- Recent analysis [L. Calibbi *et al.*, JHEP **1211**, 040 \(2012\)](#)
- Takes into account
 - LHC Higgs mass measurement
 - θ_{13} measurement
 - $Br(\mu \rightarrow e\gamma) < 2.4 \times 10^{-12}$ from [MEG \(2011\)](#)
- Compares direct LHC-2012 limits with flavor constraints

CLFV vs direct LHC searches



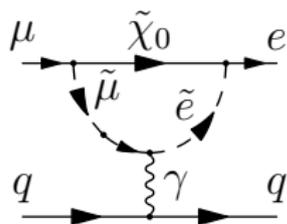
L. Calibbi *et al.*, JHEP 1211, 040 (2012)

Complementarity with the LHC

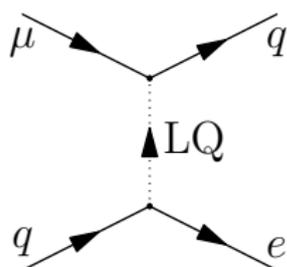
- Today's best constraints
 - Direct searches for some cases
 - CLFV for others
- If new physics is seen at LHC
 - Need CLFV measurements to discriminate models
- If no LHC signal
 - Mu2e can still make a discovery

Mu2e can discover

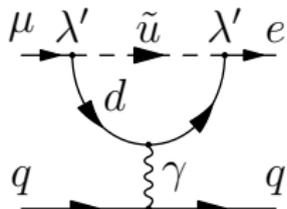
SUSY



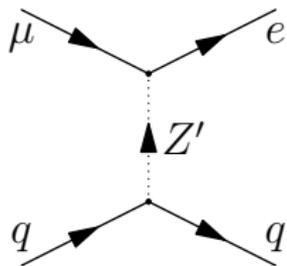
Leptoquarks



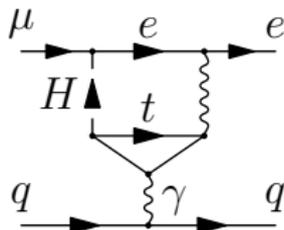
RPV SUSY



Z' /anomalous couplings



Second Higgs doublet



Extra dimensions, etc.

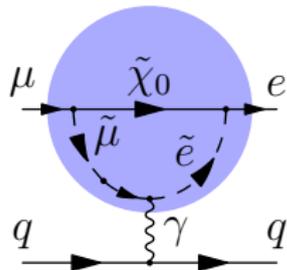
Some reviews:

Kuno, Okada, 2001

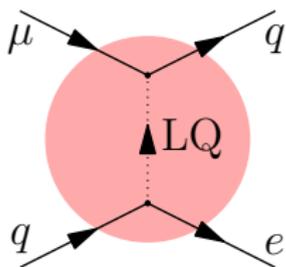
M. Raidal *et al.*, 2008

Mu2e can discover

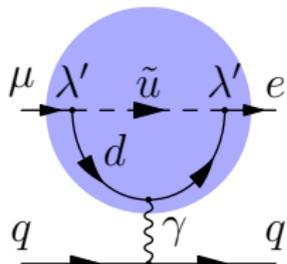
SUSY



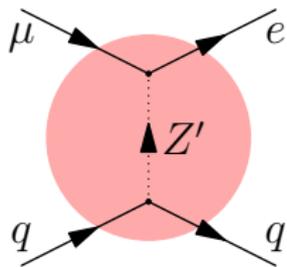
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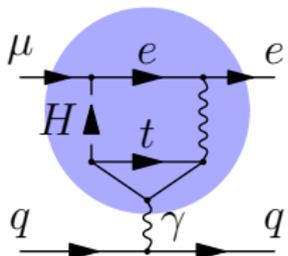
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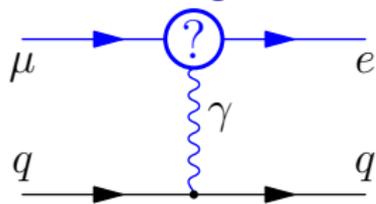
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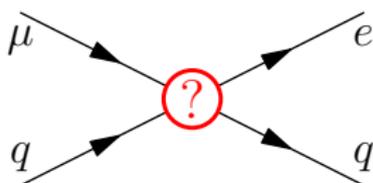
Effective theory

Electromagnetic vertex



Often gives large $Br(\mu \rightarrow e\gamma)$

Contact interaction:



May be no $\mu \rightarrow e\gamma$ signal

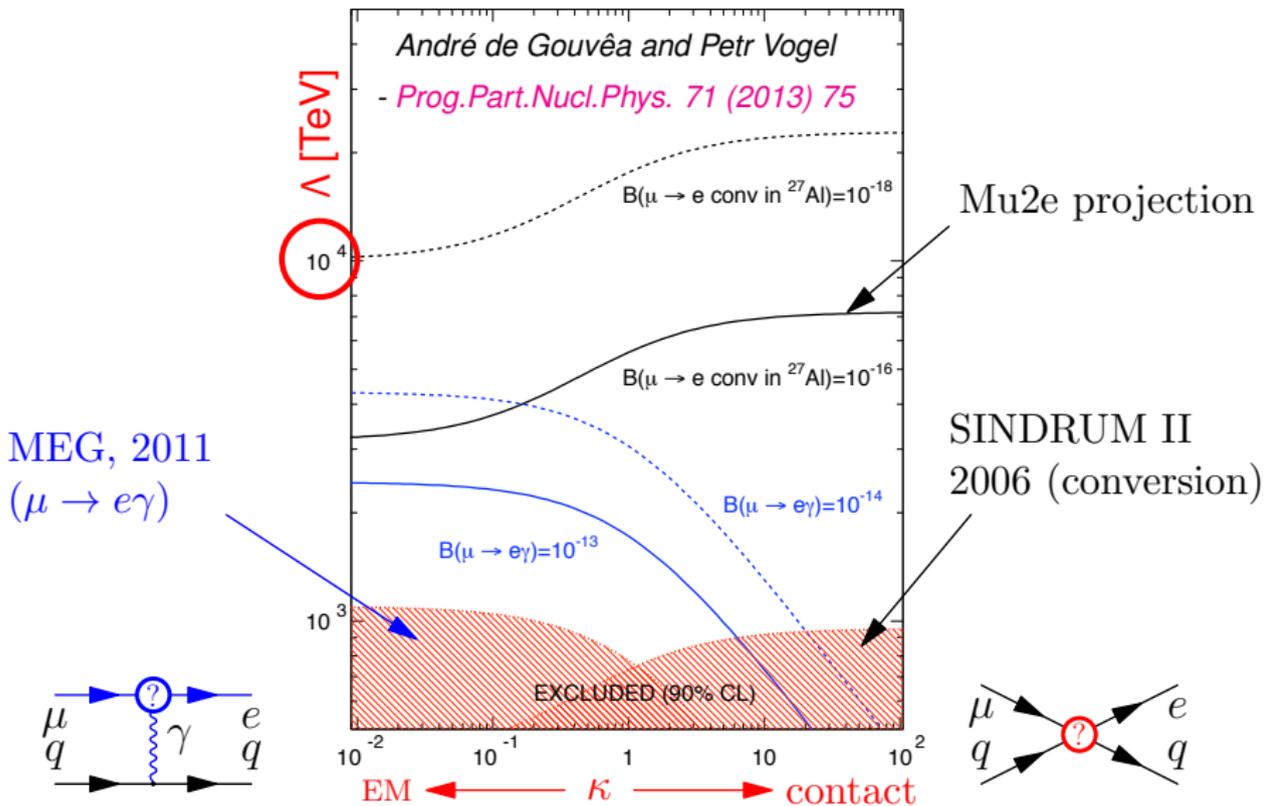
Relative rates of conversion and $\mu \rightarrow e\gamma$ are model dependent
Handle to discriminate New Physics models

Parametrization: $\mathcal{L}_{CLFV} =$

$$\frac{m_\mu}{(1 + \kappa)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

Λ : mass scale, κ : importance of contact term

Muon LVF physics reach



Mu2e experiment

Mu2e collaboration: $\gtrsim 150$ physicists



Boston University
Brookhaven National
Laboratory
LBL/UC Berkeley
University of California,
Irvine
California Institute of
Technology
City University of New York
Duke University
Fermi National Accelerator
Laboratory
University of Houston
University of Illinois

Lewis University
University of
Massachusetts,
Amherst
Muons, Inc.
Northern Illinois
University
Northwestern
University
Pacific Northwest
National Laboratory
Purdue University
Rice University
University of Virginia
University of
Washington



INFN Genova
INFN Lecce/Università del Salento
INFN Lecce/Università Marconi
INFN Pisa
Università di Udine/INFN
Trieste/Udine
Laboratori Nazionali di Frascati



Institute for Nuclear Research,
Moscow
Joint Institute for Nuclear Research,
Dubna

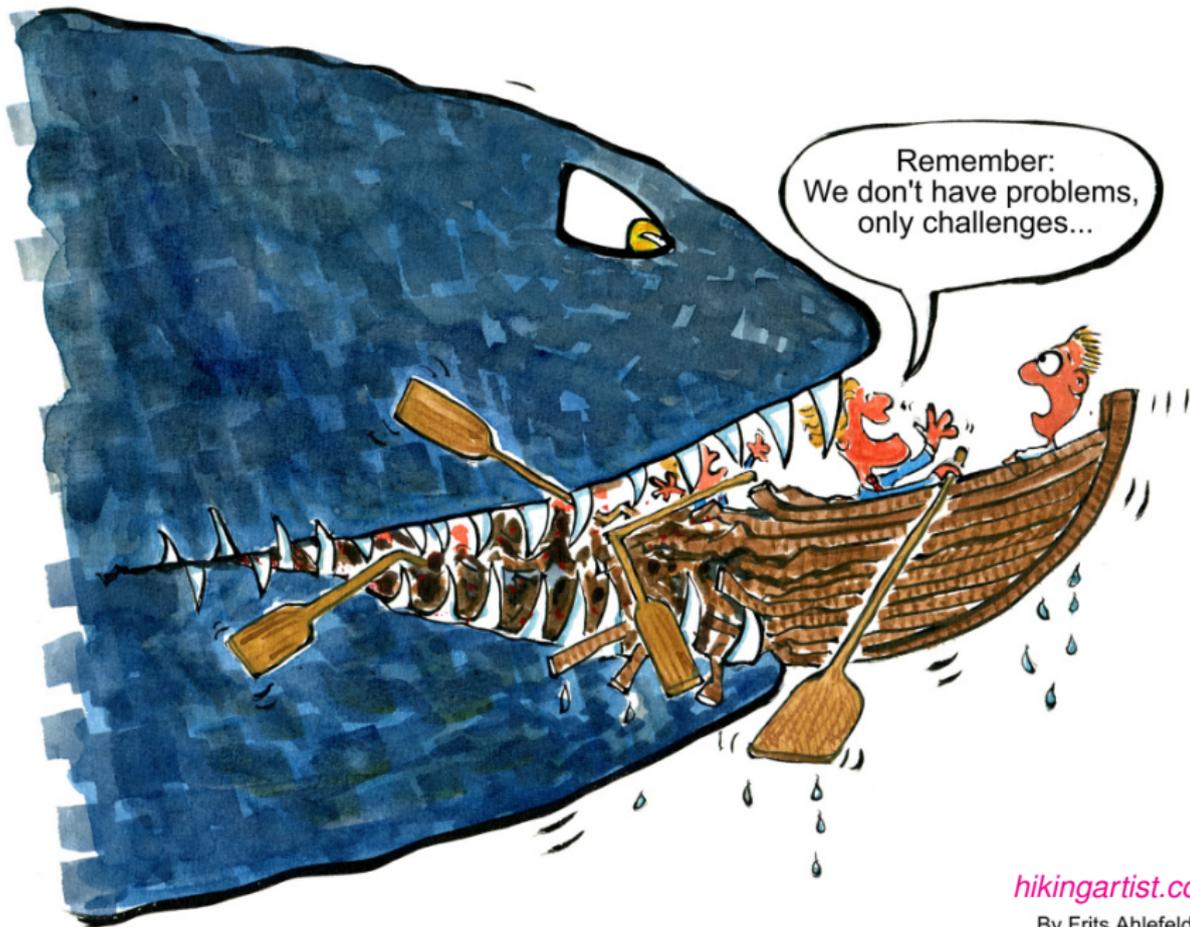
The concept of Mu2e measurement

- Generate pulsed beam of low momentum negative muons
- Stop muons in thin foils and form muonic atoms
 - μ^- in aluminum: $\tau^{\text{Al}} = 864$ ns
- Wait for prompt backgrounds to decay
- Then measure electron spectrum
 - The signal: mono-energetic electrons at 105 MeV

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Sounds straightforward. . .
But achieving a 10^{-17} sensitivity is challenging.

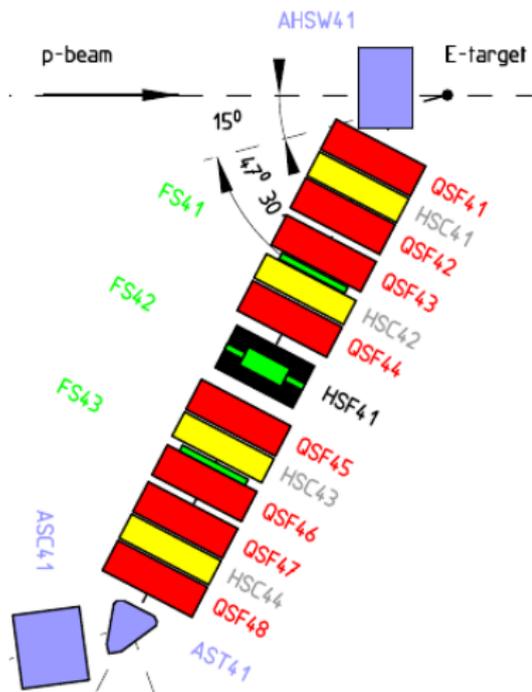


Remember:
We don't have problems,
only challenges...

Challenge: getting the muons

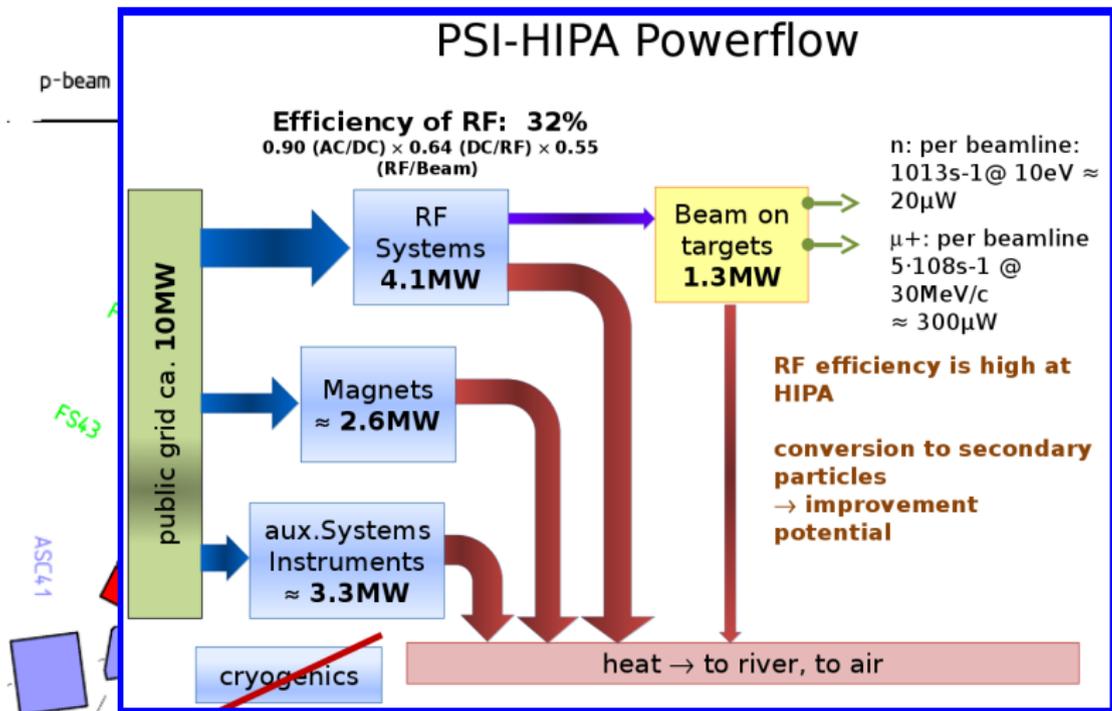
- A 10^{-17} measurement will need $> 10^{17}$ muons
 - Produced by proton beam
- SINDRUM-II: 1 MW proton beam at PSI
- Fermilab will have 8 kW of protons to spare for Mu2e
- How can we be competitive???

The usual way to collect muons



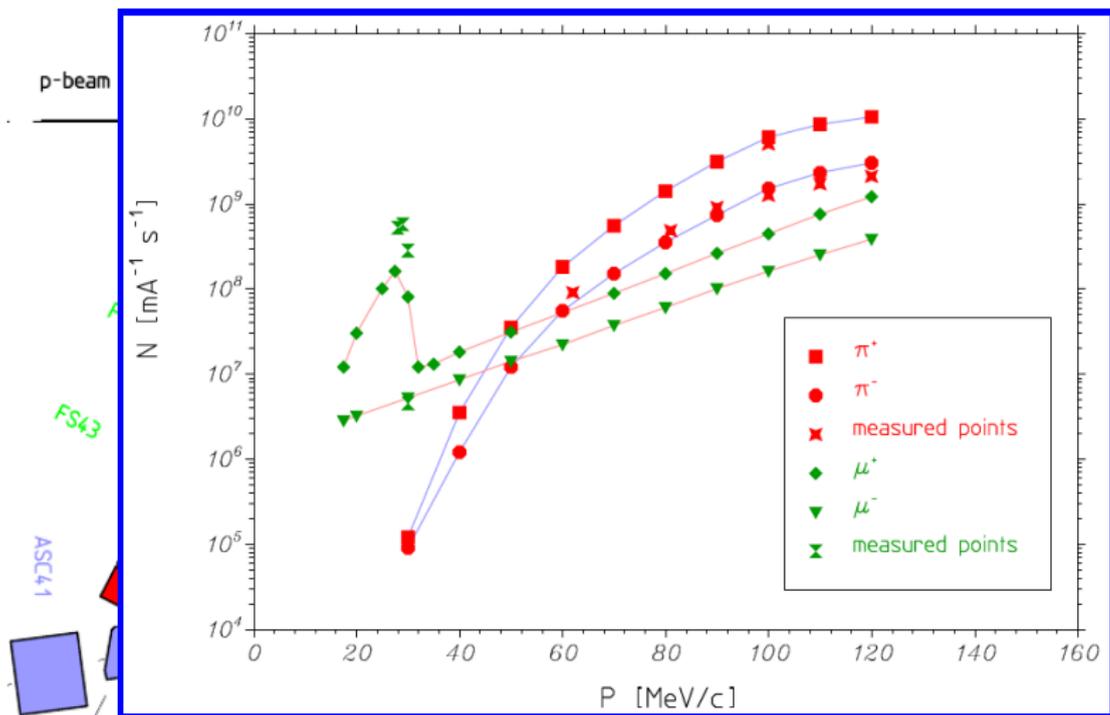
- PSI $\pi E5$ beamline
- Used by SINDRUM II

The usual way to collect muons



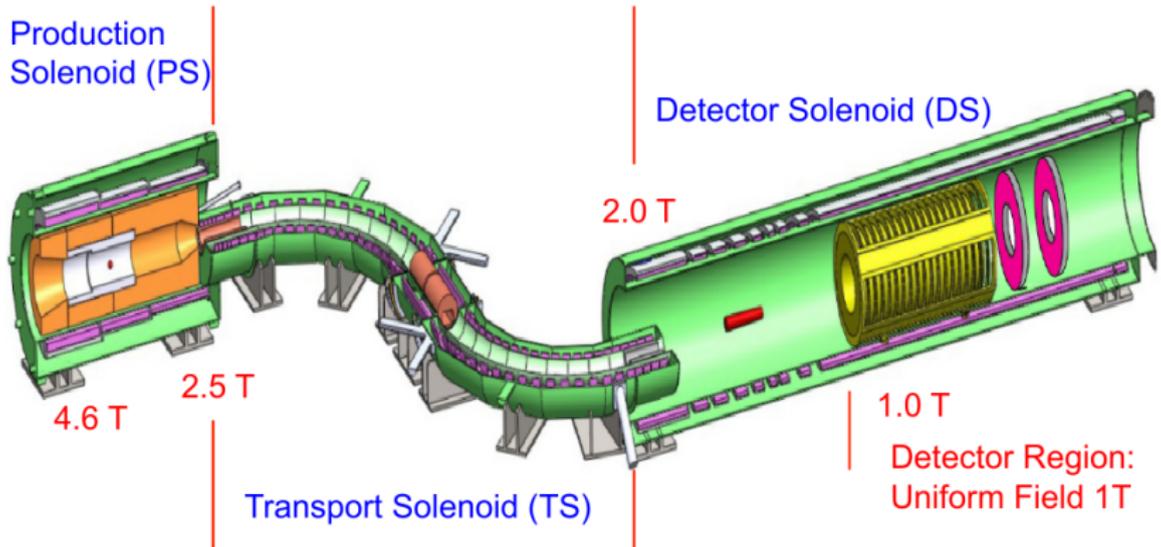
1.3 MW protons \Rightarrow 300 μW muons [M. Seidel, PSI-2013]

The usual way to collect muons



More relevant: $\mathcal{O}(10^7) \mu^-/s$ **Mu2e: $> 10^{10} \mu^-/s$**

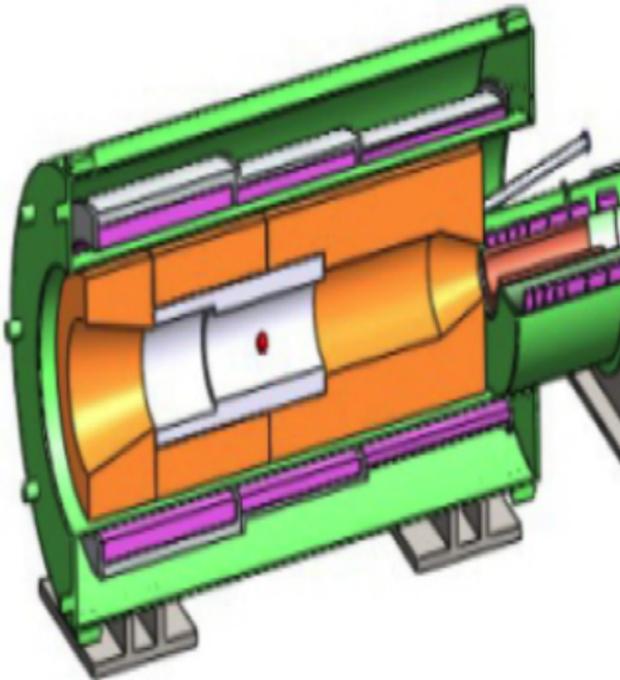
Meet Mu2e magnets



Graded B for most of length

Not shown: Cosmic Ray Veto, Extinction Monitor

Production solenoid

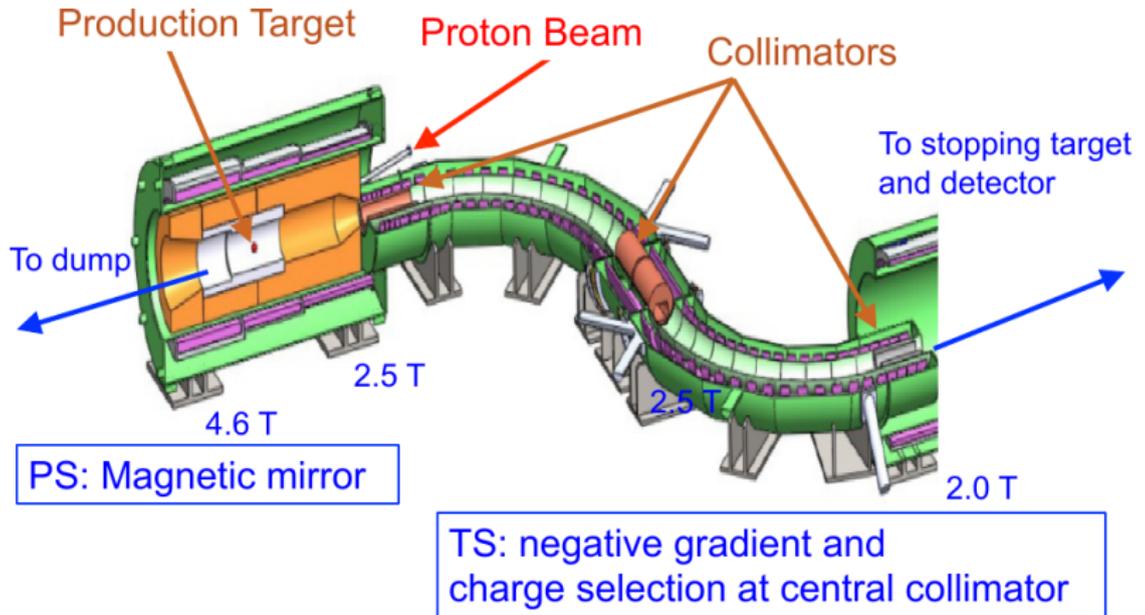


- Proton target in \vec{B} field
- Magnetic mirror
- Soft pions confined
- Collect most of resulting soft muons
- Suggested for MELC:
V. Lobashev, 1992

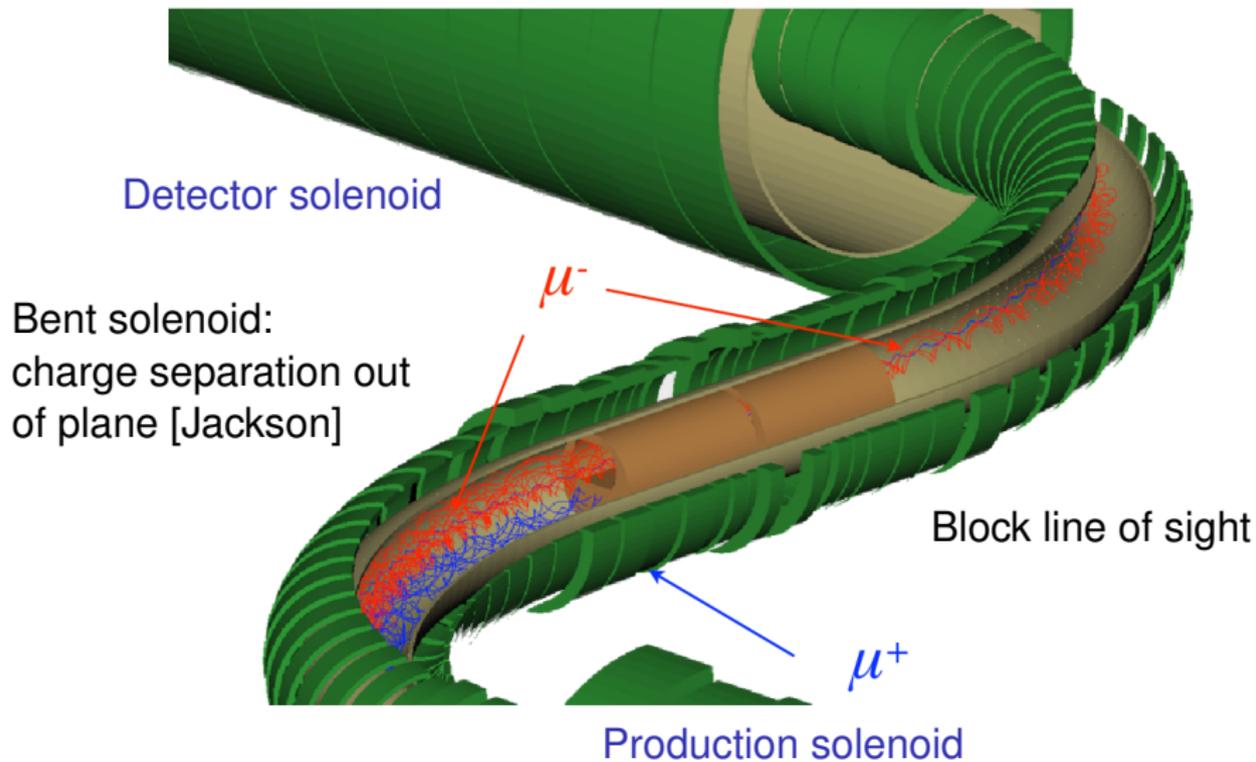
Production solenoid challenges

- 4 K superconducting coils
- Near proton target:
 - Heat
 - Radiation damage
 - cable
 - insulation
- Large volume & field:
 - $\mathcal{O}(150)$ t forces
 - Stored energy
- Target life and access

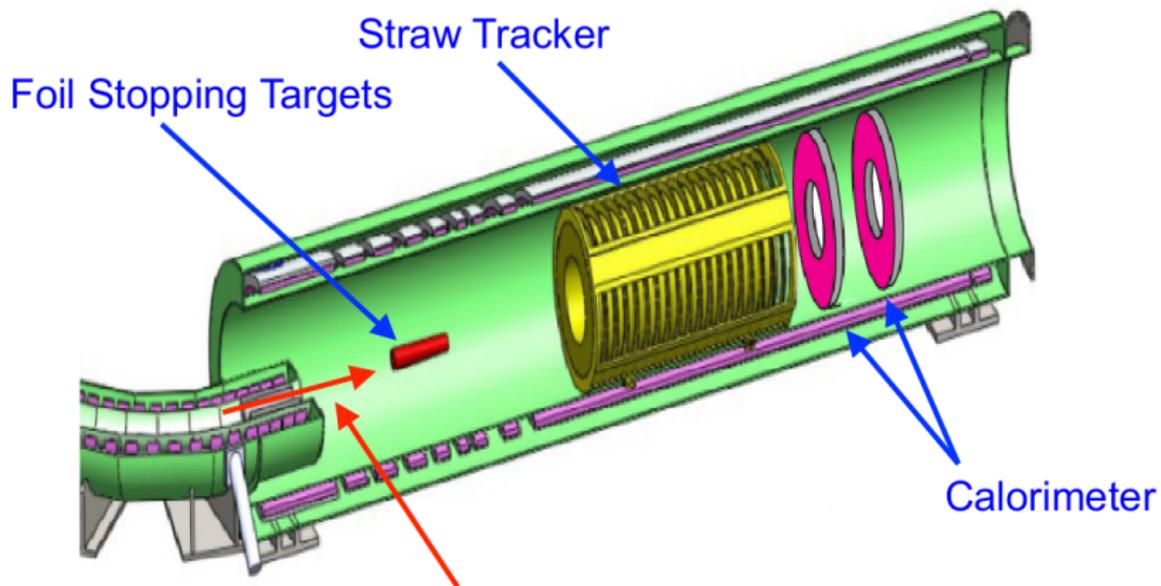
Muon production and delivery



Charge selection

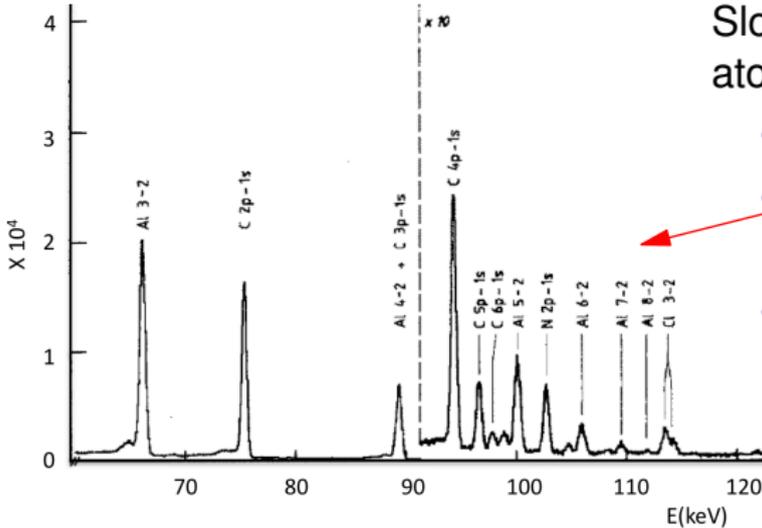


Stopping target and detectors



Incoming muon beam: $\langle \text{Kinetic Energy} \rangle = 7.6 \text{ MeV}$

Muons stopping in Al target



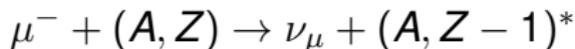
Slow down, form muonic atoms, cascade to 1s state

- picoseconds time scale
- X-rays: use to count stopped muons
- Derive number of captures for normalization

$$R_{\mu e} = \frac{\Gamma[\mu^- + (A, Z) \rightarrow e^- + (A, Z)]}{\Gamma[\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)^*]}$$

Muonic aluminum atom

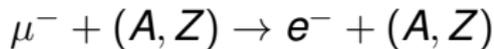
- 61% Capture:



- 39% Decay in orbit (DIO):

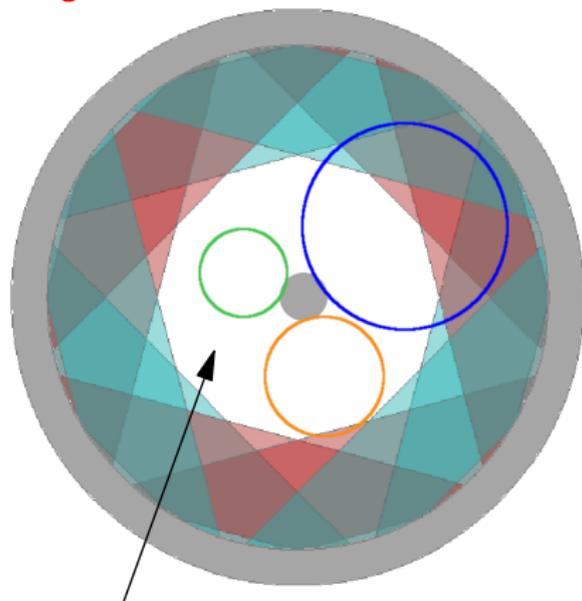
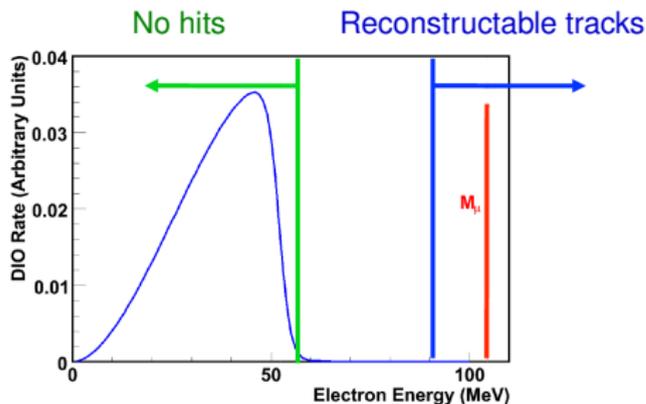


- Intrinsic background—scales with number of muons
 - Drives momentum resolution requirements
-
- New Physics: conversion?



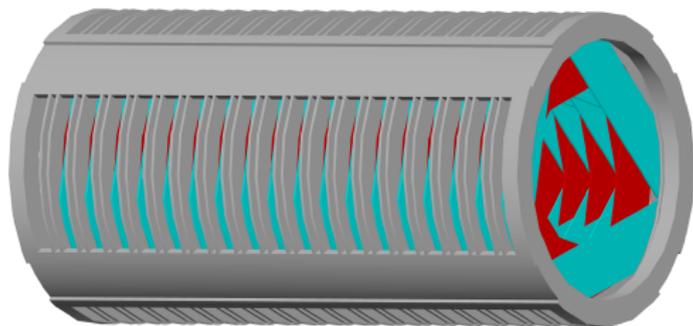
How to handle detector rates from 10^{10} muons/s?

Be blind to most tracks: **annular design**



Vacuum: no scattering

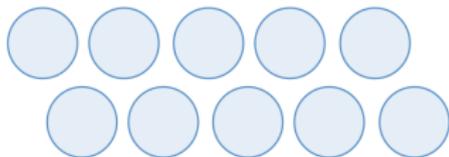
Tracker



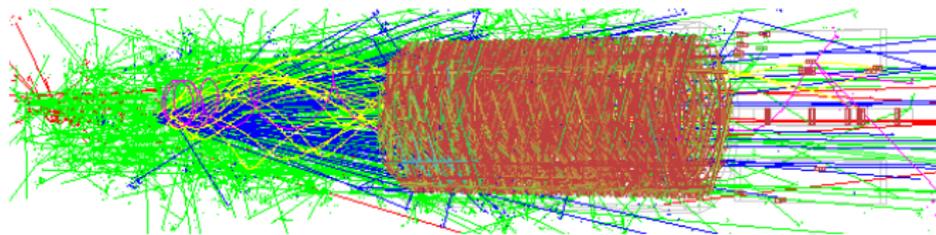
- about 3 m long
- 1 T uniform B field
- “Good” tracks make 2–3 turns

21,600 straw tubes

- 5 mm diameter
- $15\ \mu\text{m}$ wall
- $25\ \mu\text{m}$ wire
- in vacuum

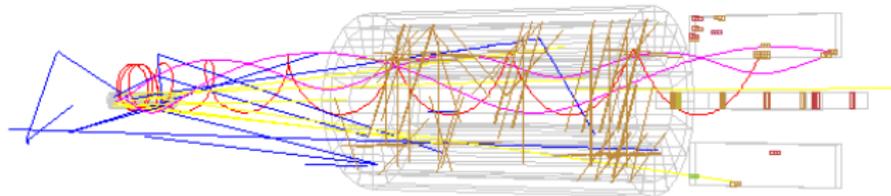


Pattern recognition



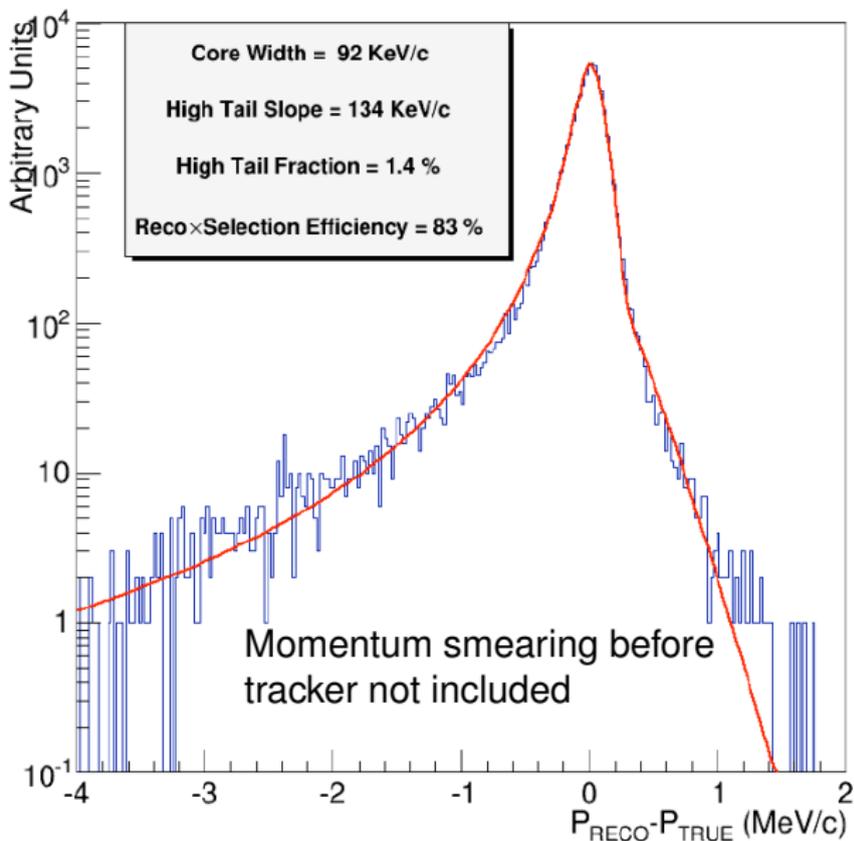
Single proton pulse: particles and hits in 500–1694 ns

Pattern recognition



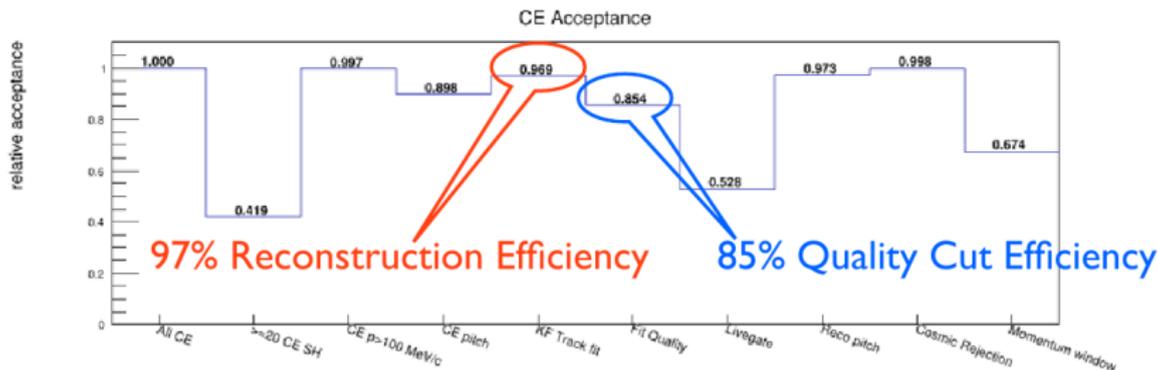
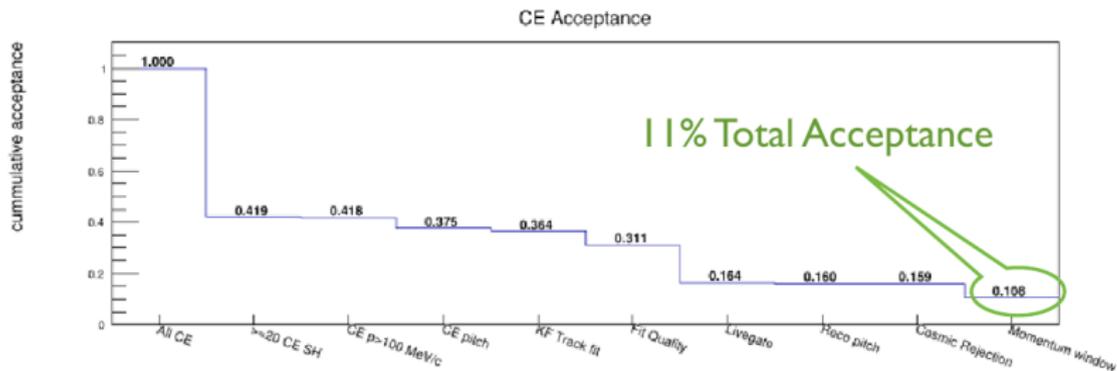
Single proton pulse: particles and hits in ± 50 ns around conversion

Tracker momentum resolution



Dave Brown, CLFV2013 (Lecce)

Signal reconstruction efficiency

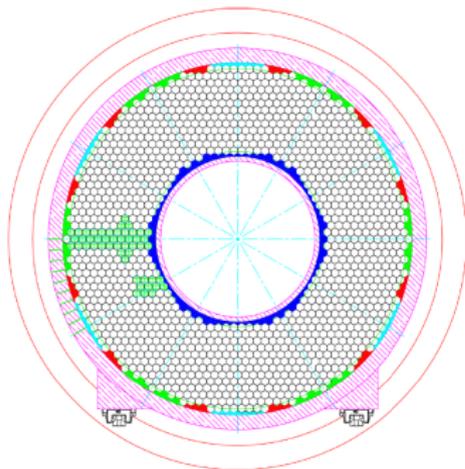
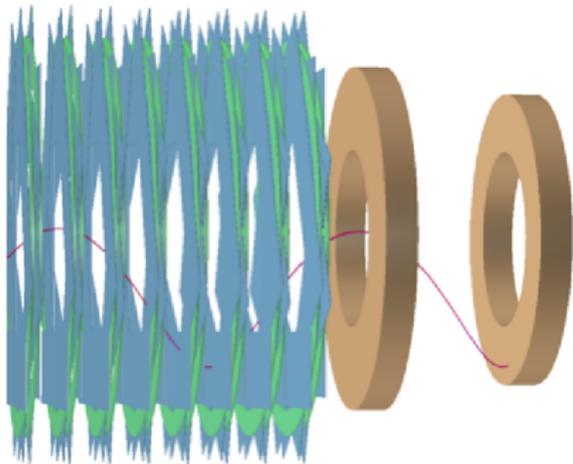


Dave Brown, CLFV2013 (Lecce)

Calorimeter

Two disk geometry

Hex BaF crystals
SiPM or APD readout



Provides precise timing, PID, alternate track seed, possible calibration trigger.

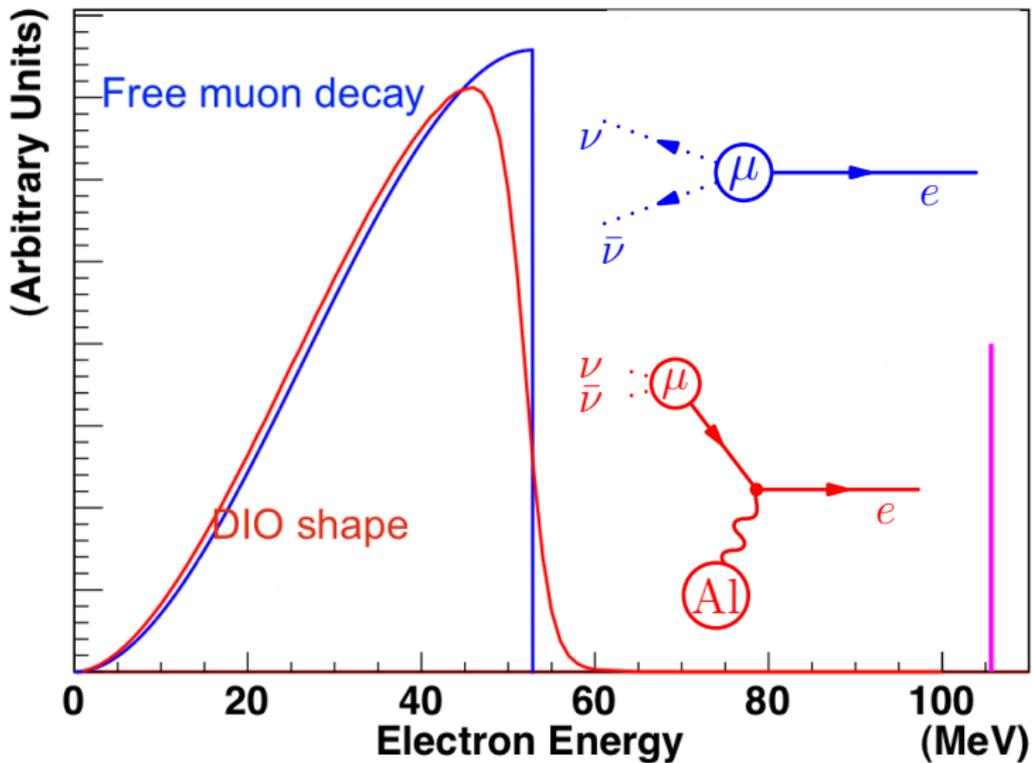
Makes sure signal candidates are not catastrophic misreconstructions.

Got our signal. What about backgrounds?

Types of backgrounds

- Muon induced
 - Muon decay in orbit (DIO)
- Out-of-time protons or long transit secondaries
 - Radiative pion capture
 - Muon decay in flight
 - Pion decay in flight
 - Beam electrons
 - Antiprotons
- Cosmic rays

Electron spectra



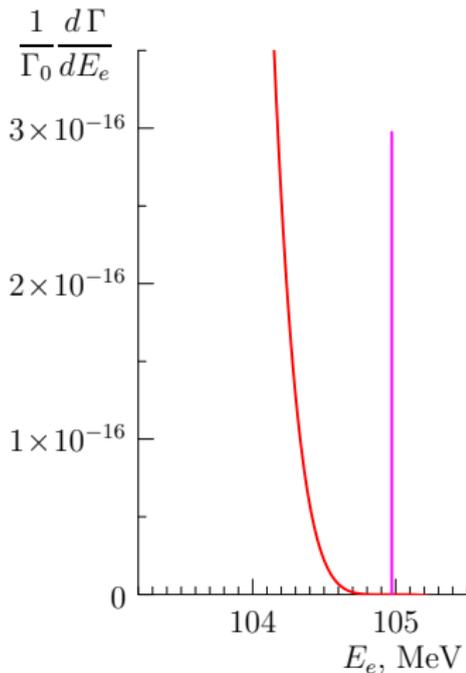
A closer look at DIOs

- Latest spectrum computation:
Czarnecki, Tormo, Marciano (2011)
- End point expansion

$$\frac{1}{\Gamma_0} \frac{d\Gamma}{dE_e} = B \left(E_\mu - E_e - \frac{E_e^2}{2m_N} \right)^5$$

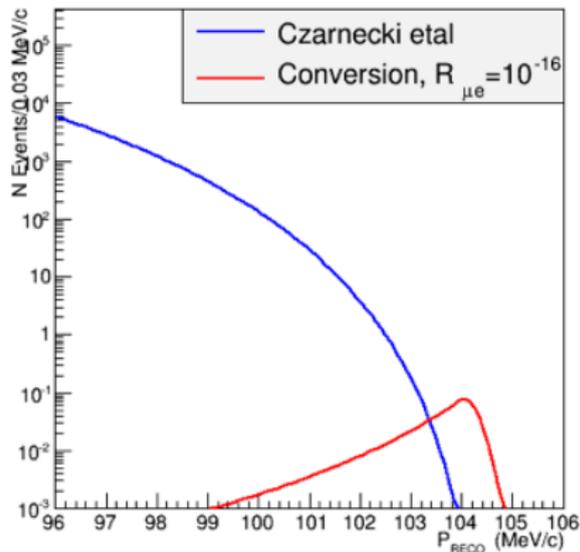
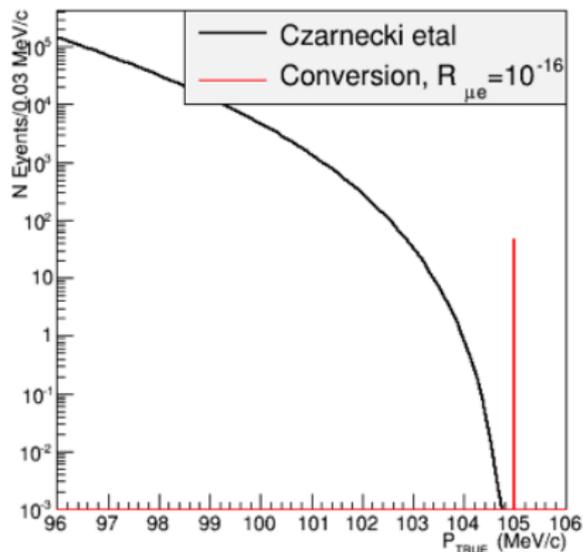
— **small but steep tail!**

- DIO electron differs from signal only by its p



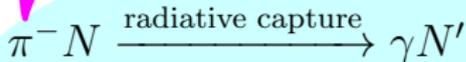
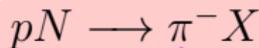
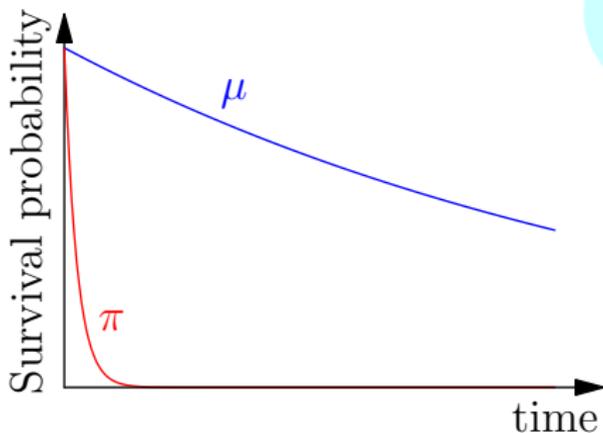
Momentum resolution is important!

Especially the high side tail: pushes DIOs into the signal region



Prompt backgrounds

- Signal is a 105 MeV electron
- Many ways for 8 GeV protons to make those
- Example: Radiative Pion Capture

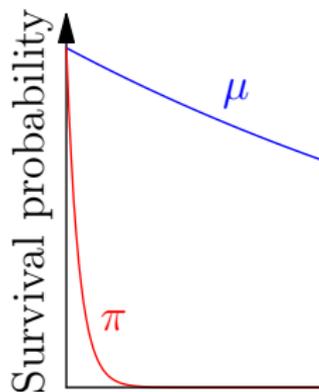


Processes in Al target

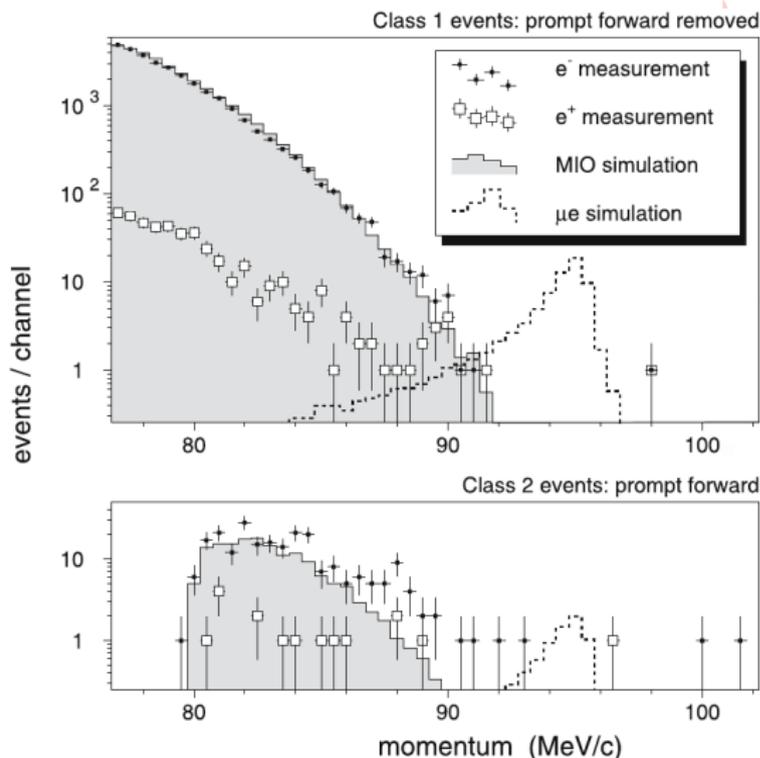
⇐ Mitigation: wait

Prompt backgrounds

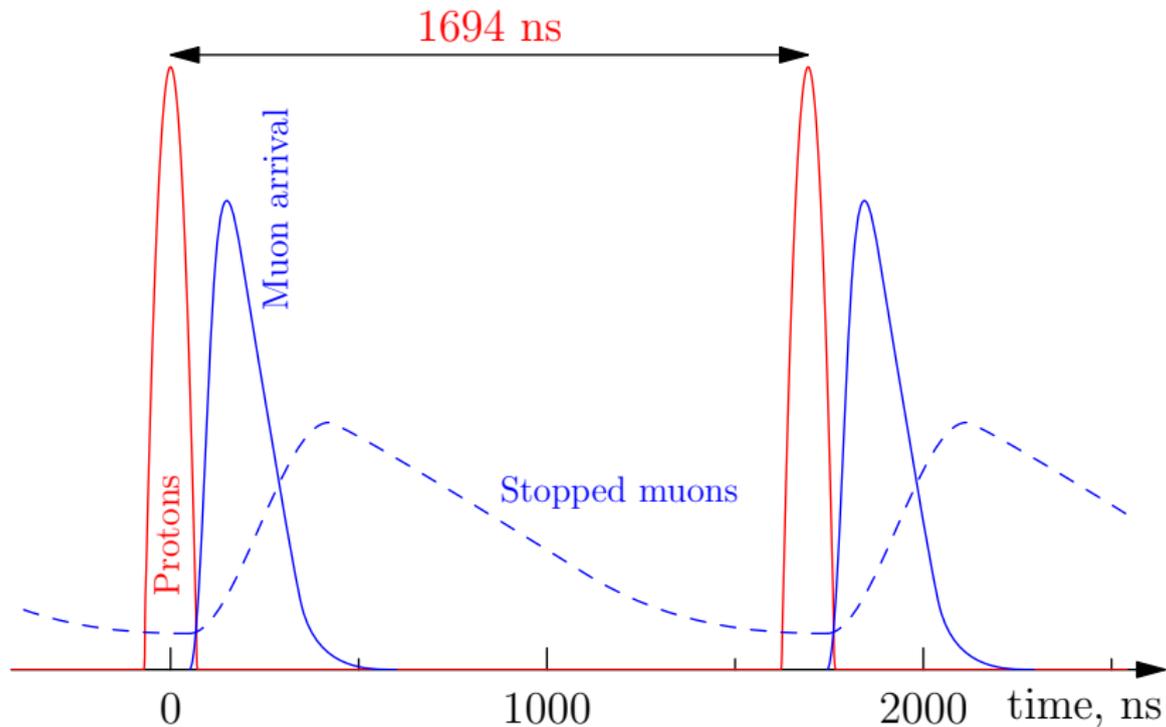
- Signal is a 105
- Many ways for to make those
- Example: Radi Capture



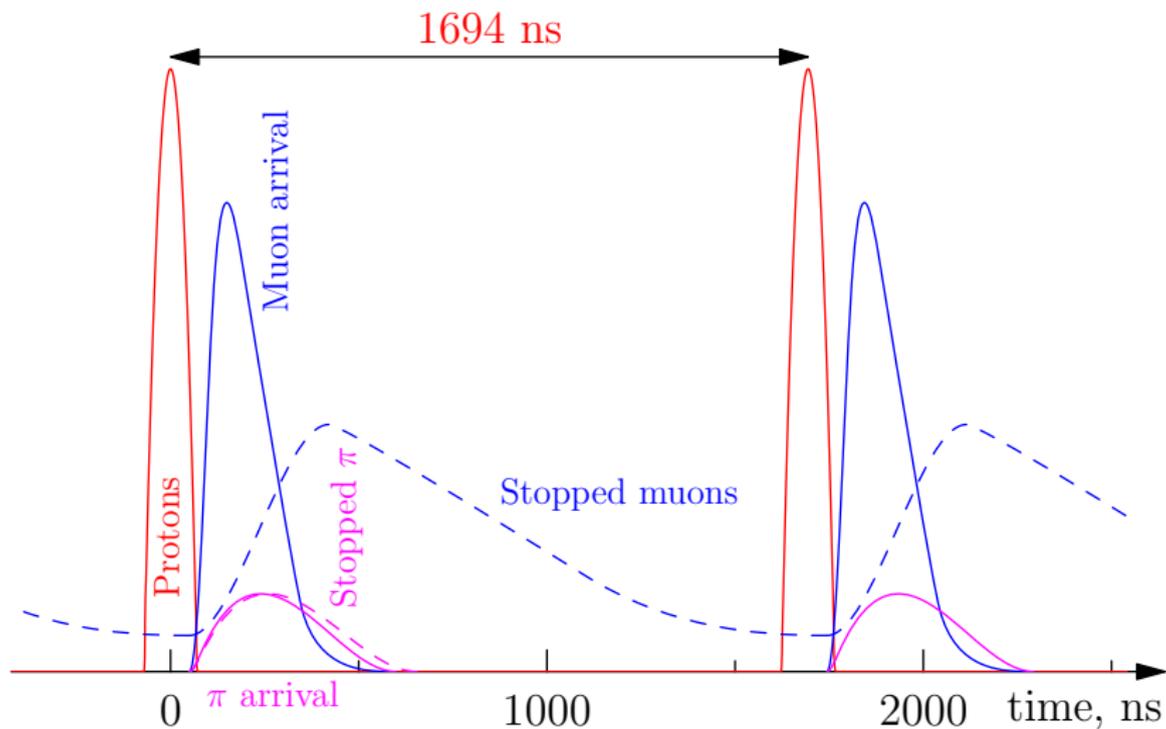
SINDRUM-II spectra



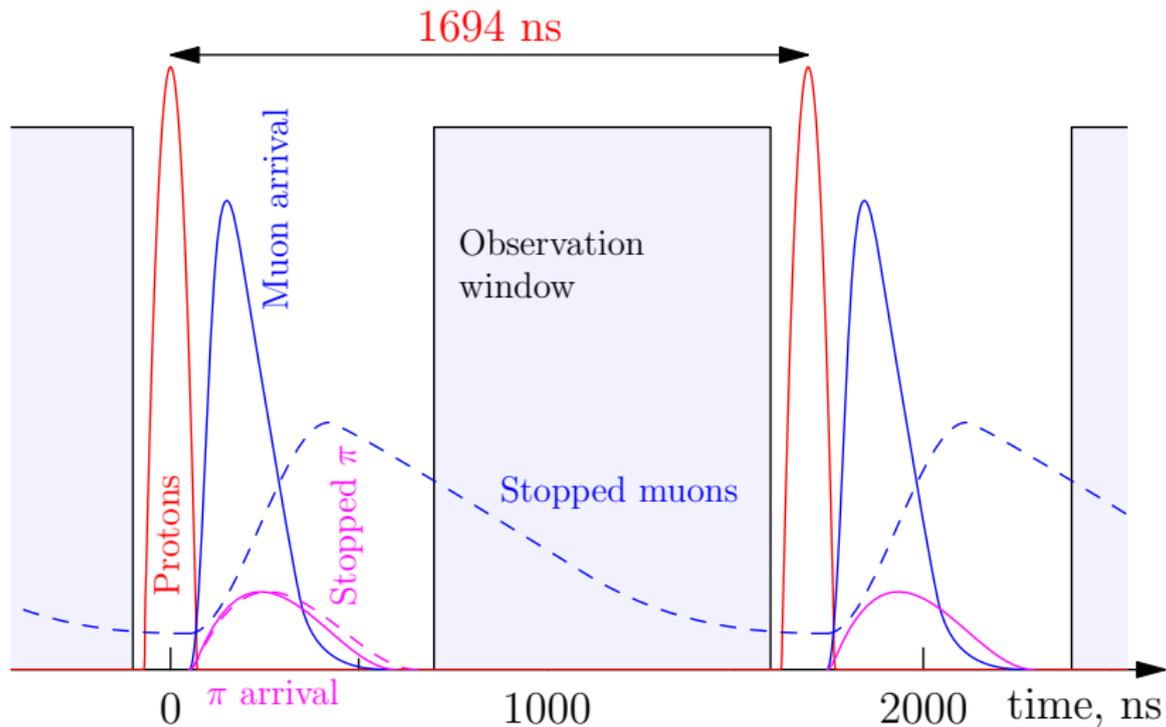
Mu2e time structure



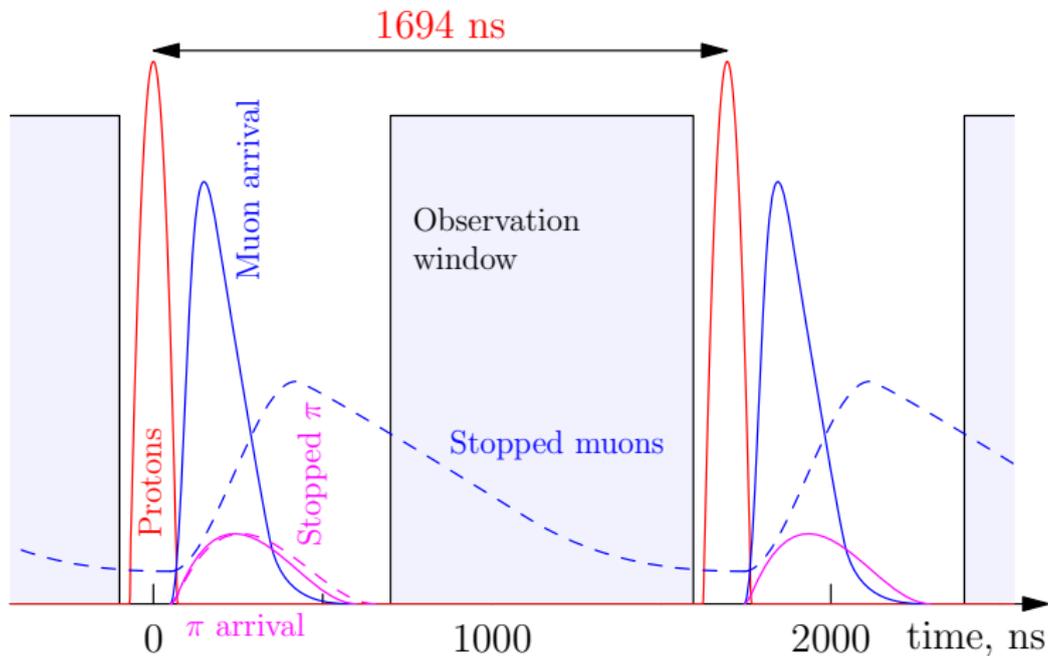
Mu2e time structure



Mu2e time structure



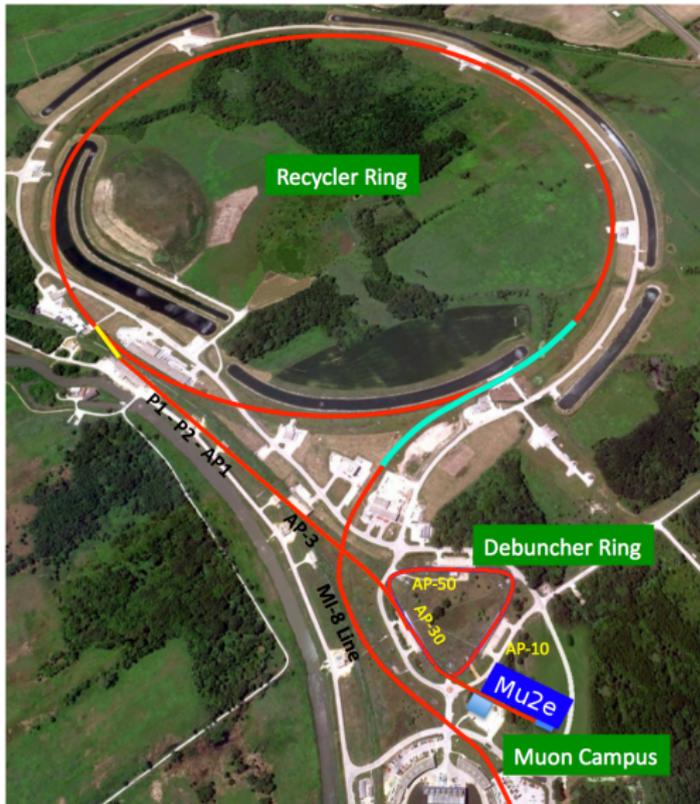
Proton beam extinction



Beam extinction requirement

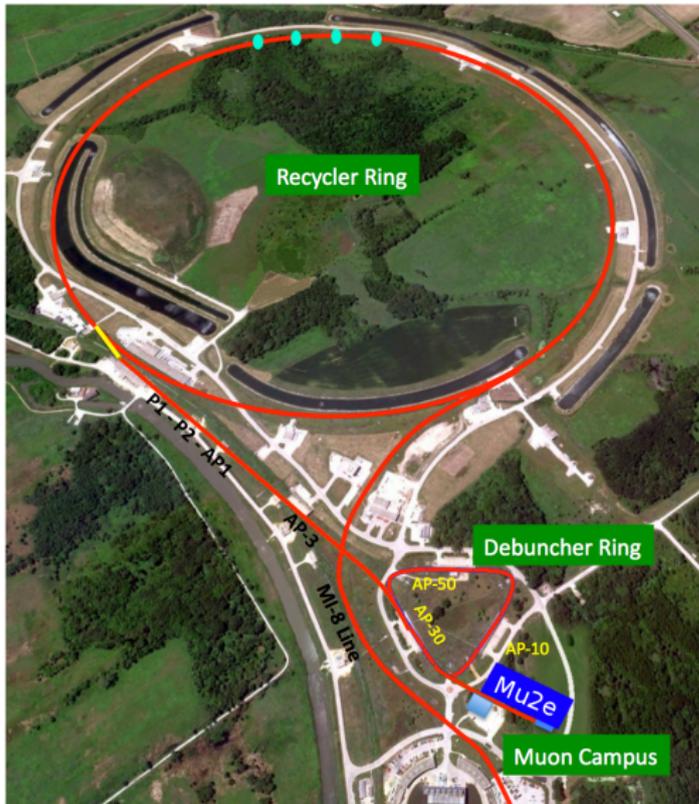
$$\epsilon = (\text{Num protons between pulses}) / (\text{Num in pulses}) < 10^{-10}$$

Proton delivery



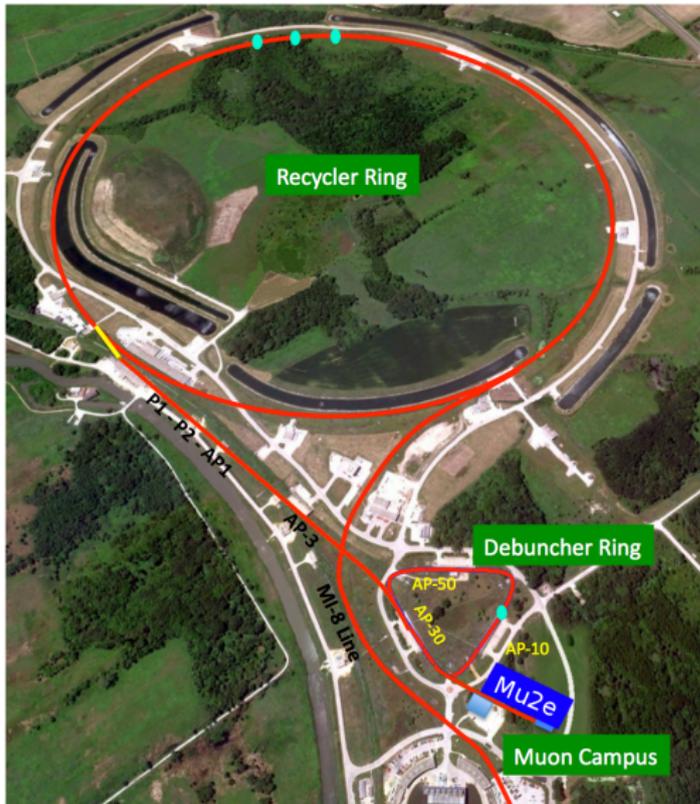
- Efficient reuse of Tevatron infrastructure
- Muon campus: former antiproton complex
 - g-2 and Mu2e
- A muon experiment can run simultaneously with NOvA
- Ring revolution period is 1694 ns: good match to $\tau^{Al} = 864$ ns

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Achieving $\epsilon = 10^{-10}$: two stages

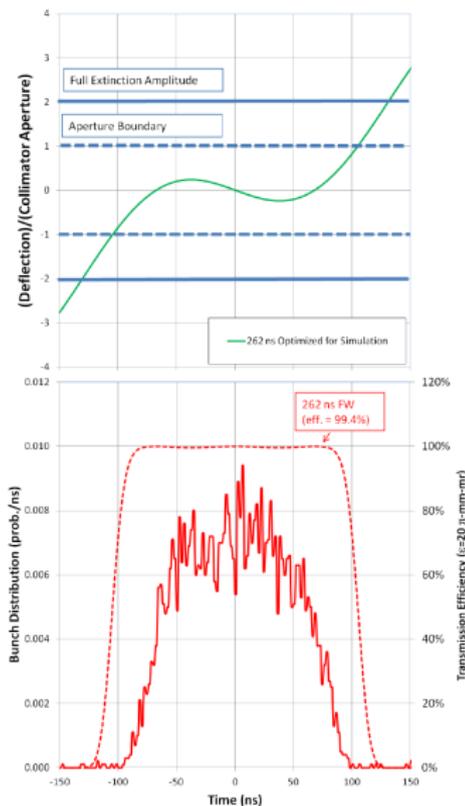
In delivery ring: better than 10^{-4}

- 1 bunch circulates at a time
- At injection $\epsilon \approx 10^{-5}$
- Degrades during slow extraction
 - RF noise, beam gas, ...

Extraction beamline: $\times 10^{-7}$

Deflect late beam with extinction magnets

- 600 kHz bunches: beyond state of art for kickers
- Use resonant dipoles 300 kHz and 5100 kHz



How to measure $\epsilon = 10^{-10}$

One could try

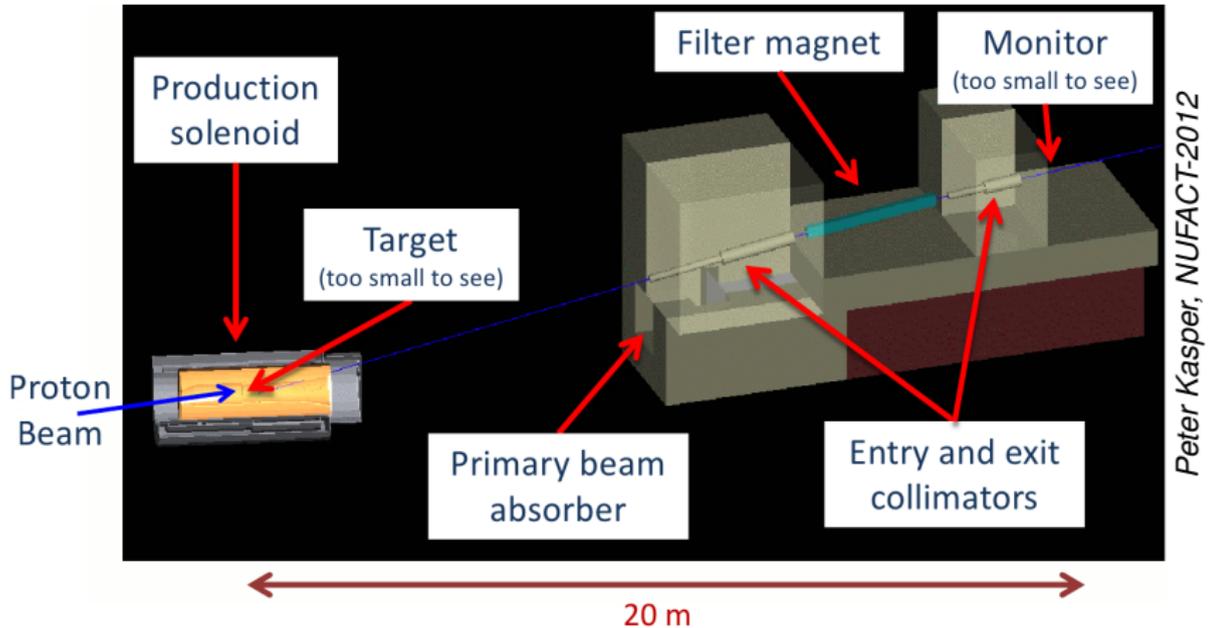
- Count 3×10^7 protons during ≈ 150 ns pulse
- Be sensitive to single proton for the rest of 1694 ns cycle
 - With background $\ll 10^{-3}$ counts/cycle

Mu2e approach: use statistical sampling instead

- Count $\mathcal{O}(30)$ secondary tracks/pulse
- Integrate over $\mathcal{O}(10^9)$ cycles ($\lesssim 1$ hour)
 - Get 3 out of time secondary tracks/integration at $\epsilon = 10^{-10}$
- Need $\ll 1/\text{integration} = 10^{-9}/\text{cycle}$ backgrounds
 - While monitoring the high intensity proton beam!

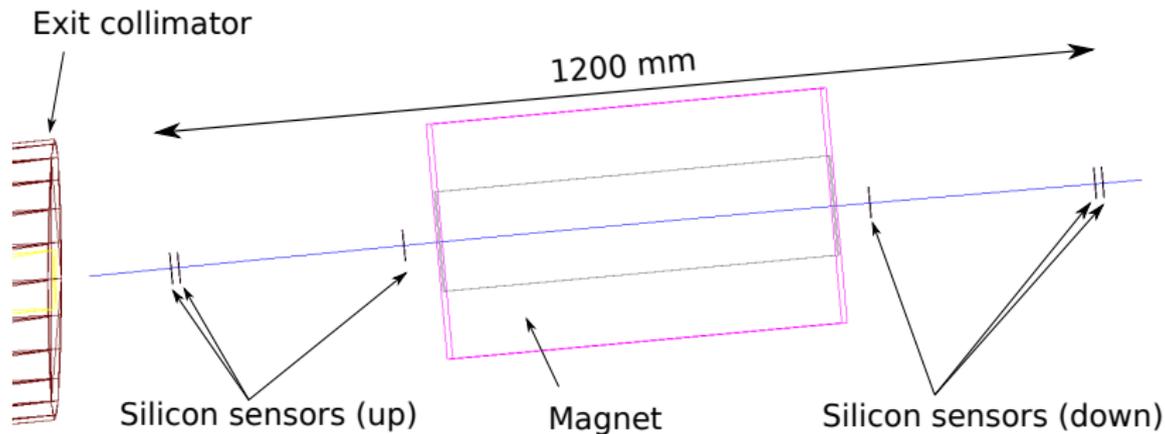
Extinction monitor

- Select positive tracks of a few GeV/c originating in the proton target with collimators and a permanent magnet



Extinction monitor

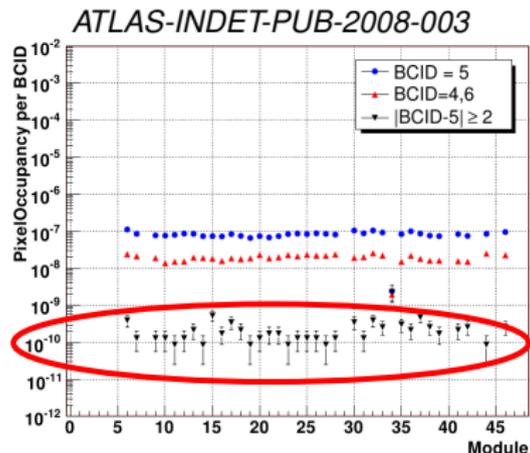
- Observe the tracks with a magnetic spectrometer



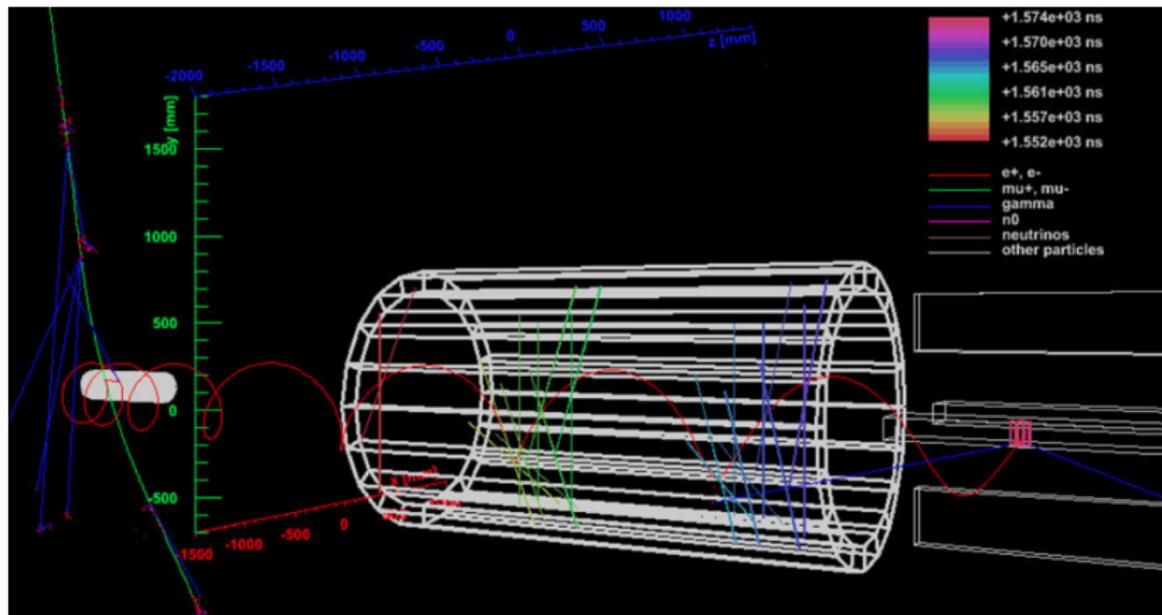
Candidate ExtMon detector technology

Silicon pixels

- demonstrated noise level
 10^{-10} hit/pixel/25 ns
- Radiation hard
- Fine granularity helps to fight backgrounds
- FE-I4 ATLAS IBL upgrade chip is a good match

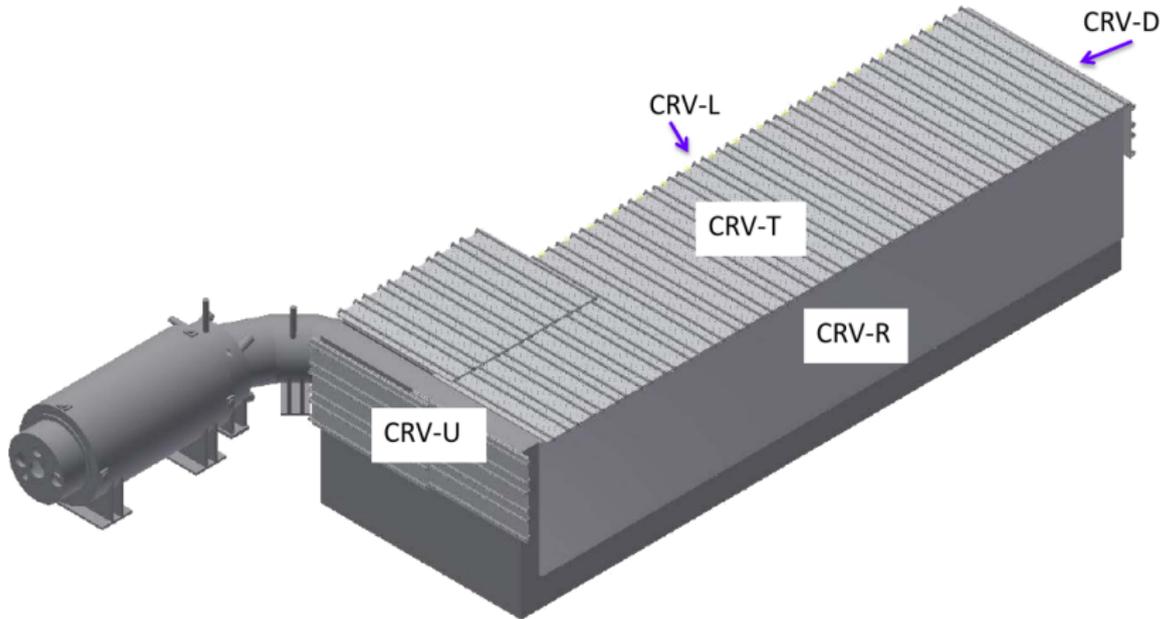


For 10^{-17} need to reject cosmic rays



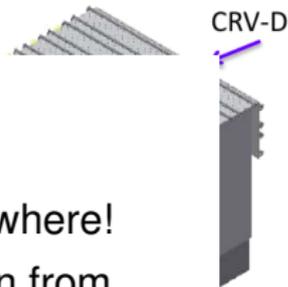
~ 1 event/day

Cosmic ray veto



- Surround detector with scintillator counters
- Require 99.99% veto efficiency

Cosmic ray veto

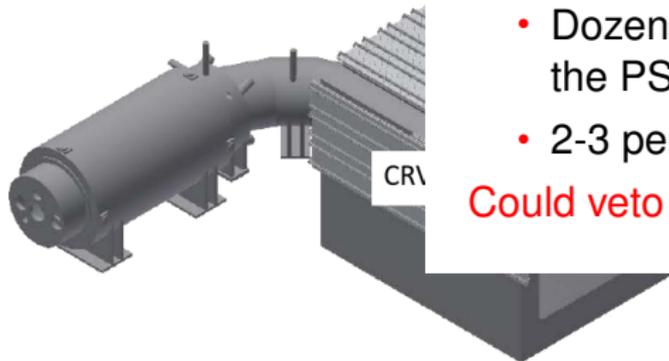


CRV Challenge

Neutrons and γ everywhere!

- Dozens per proton from the PS
- 2-3 per captured muon

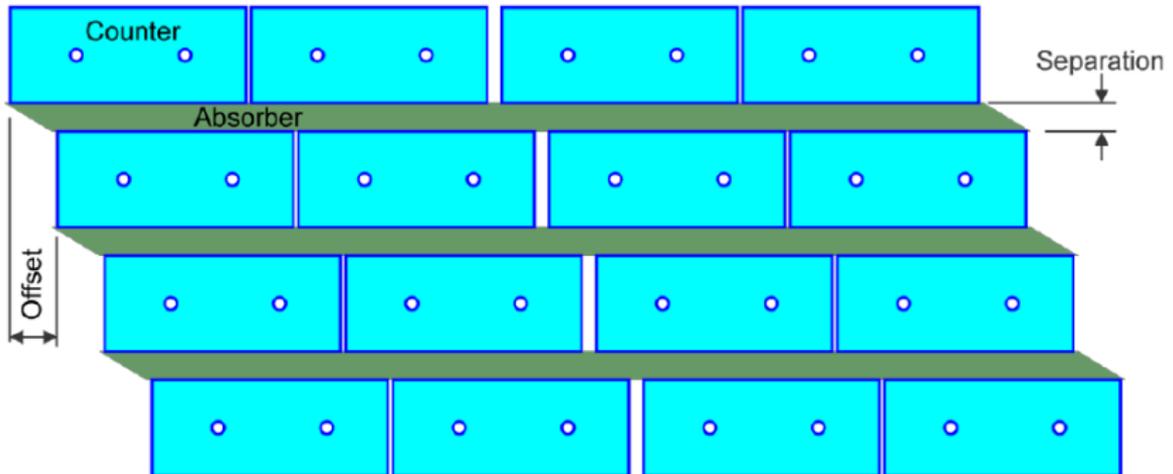
Could veto 100% of time!



- Surround detector with scintillator counters
- Require 99.99% veto efficiency

CRV mitigation

- Shielding. Lots of it.
- 4 layers, require 3-layer coincidence
- Absorber between layers: reduce correlated hits



Antiprotons

A source of background

- Negative—go through muon beamline
- Do not decay
- Heavy \implies slow
 - Arrive during signal window **even for perfect beam extinction**
 - **2 GeV shower**

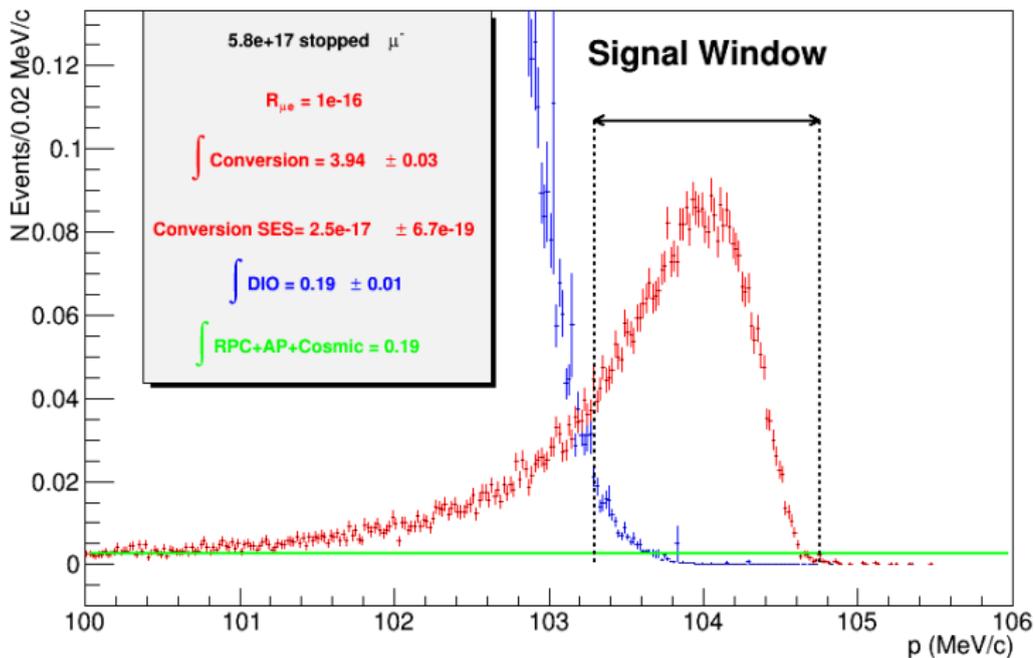
Mitigation

- Thin window in the central collimator
- Reduces muon yield
- But effectively annihilates \bar{p}

Avoidable: would be nice to have lower energy p beam!

Mu2e signal sensitivity for 3 year run

Reconstructed e^- Momentum



≈ 4 signal for $R_{\mu e} = 10^{-16}$ over 0.4 background

Summary of backgrounds

3 years of 1.2×10^{20} protons/year (8 kW beam power)

Background description	Expected events
Muon decay in orbit	0.20 ± 0.06
Antiproton induced	0.10 ± 0.06
Radiative pion capture*	0.04 ± 0.02
Cosmic rays**	0.050 ± 0.013
Beam electrons*	0.001 ± 0.001
Muon decay in flight*	0.010 ± 0.005
Total	0.4 ± 0.1

* Assuming 10^{-10} beam extinction

** For 10^{-4} cosmic ray veto inefficiency

Summary of backgrounds

Another challenge: simulations...

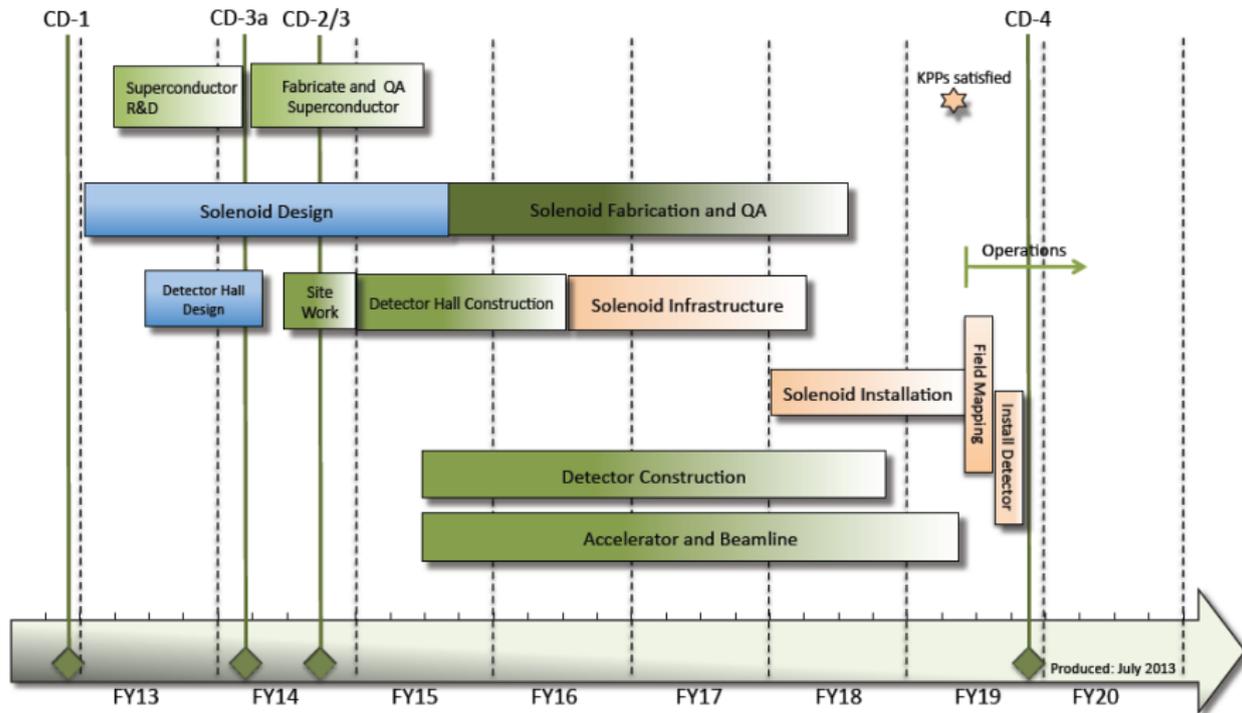
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** For 10^{-4} cosmic ray veto inefficiency

Schedule



Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent **physics potential**
 - Aims for **4 orders of magnitude improvement**:
 $R_{\mu e} \approx 2 \times 10^{-17}$ **single event sensitivity**
 - New physics reach: Λ_{eff} up to **thousands of TeV**
- Conceptual design complete **Mu2e CDR arXiv:1211.7019**
(DOE CD-1 in July 2012)
- Working towards technical design
- Data taking: about 2019

<http://mu2e.fnal.gov>

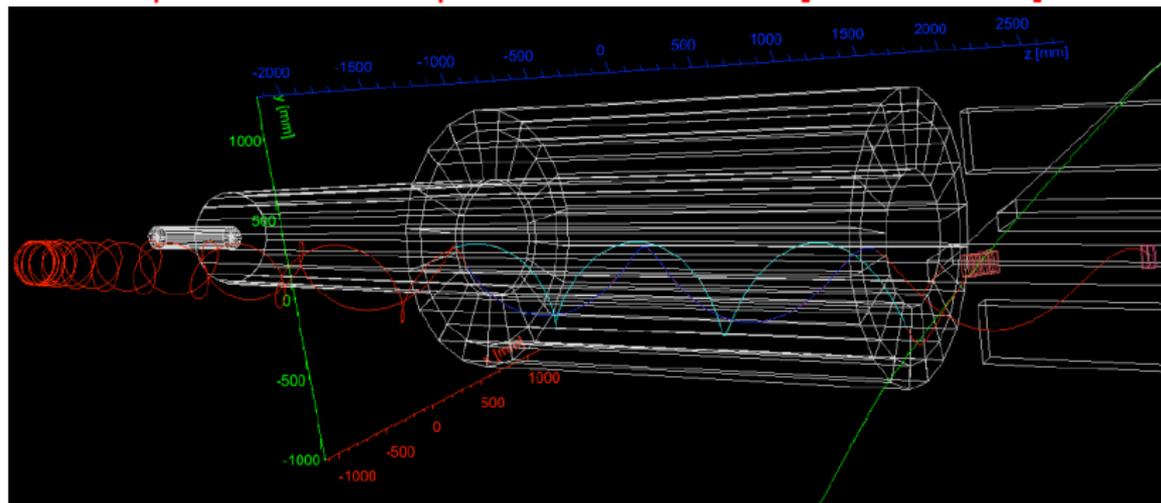
We'll handle our challenges!



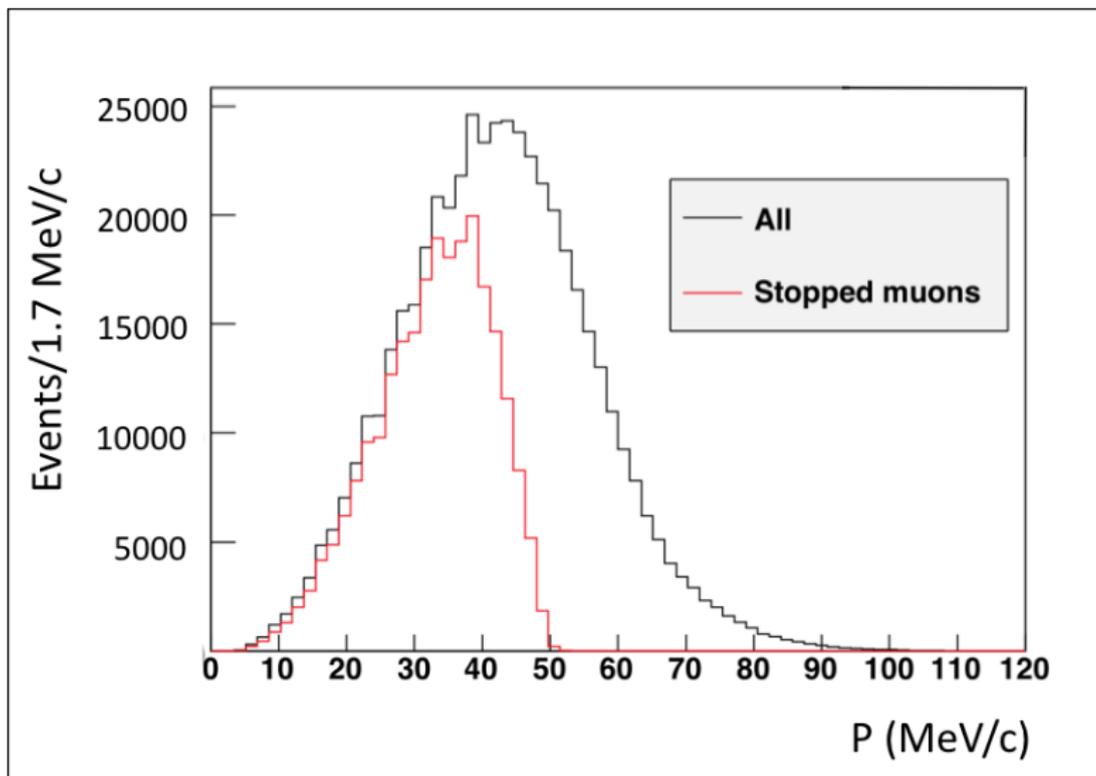
Extra slides

Tracker energy loss calibration

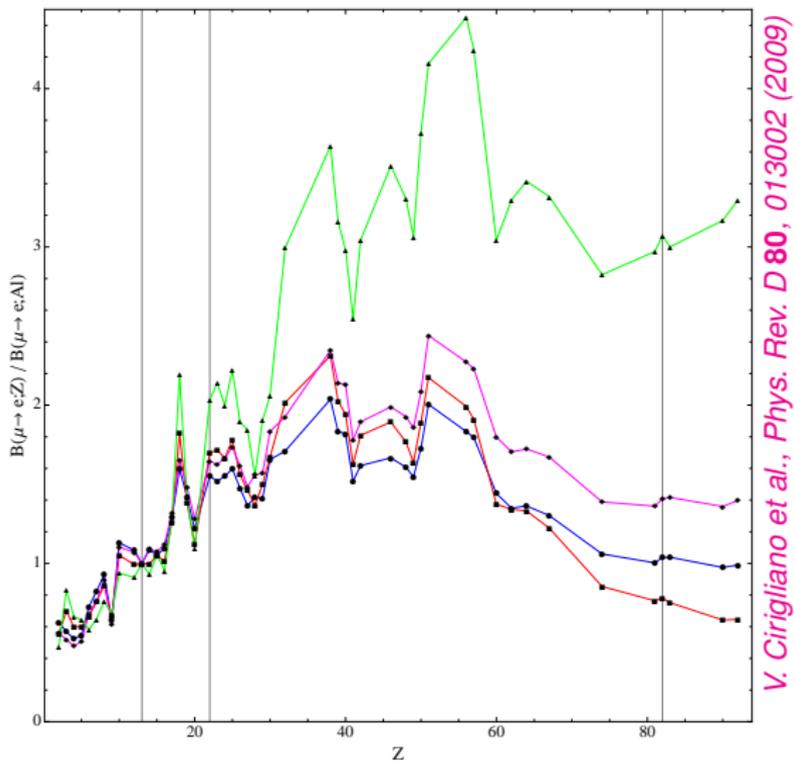
Double-pass of cosmic produced electrons [Dave Brown]



Muon momentum at the stopping target



Target Z dependence



V. Cirigliano et al., Phys. Rev. D **80**, 013002 (2009)